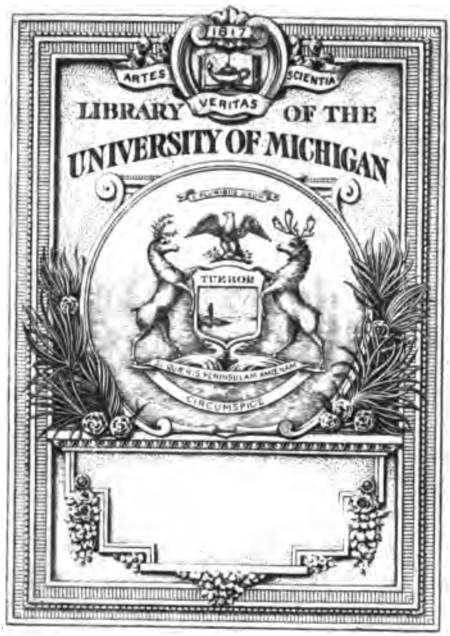
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LESSONS IN

PRACTICAL ELECTRICITY

PRINCIPLES, EXPERIMENTS, AND
ARITHMETICAL PROBLEMS

AN ELEMENTARY TEXT BOOK

BY C.harles WALTON SWOOPE

ASSOCIATE MEMBER AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
LATE INSTRUCTOR OF APPLIED ELECTRICITY AT THE
SPRING GARDEN INSTITUTE, PHILADELPHIA

WITH OVER 400 ILLUSTRATIONS

FIFTEENTH EDITION
Thoroughly Revised and Enlarged
With Complete Revision of Chapter on

ELECTRIC LIGHTING

By HARRY NOYES STILLMAN
Instructor at the Spring Garden Institute, Philadelphia

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PREFACE

Several years ago the author prepared a private edition of "Lessons in Practical Electricity," which was published by the Spring Garden Institute for the use of its evening classes in practical electricity.

The demand for the book arose from two facts: First, these classes, being composed of young men engaged in various occupations who desired to obtain a beginner's knowledge of the principles and arithmetic of applied electricity, were very large; second, an unsuccessful attempt was made to obtain a book suitable for thoroughly supplementing a combined course of lectures and individual laboratory work.

The educational success attained at the Institute, and also at several other schools which secured the privilege of obtaining copies of the edition (now exhausted), and the fact that the former situation had again to be met, seemed to warrant the preparation of the present volume, which has been entirely rewritten and several hundred new illustrations introduced.

In day and evening schools of applied sciences the lecture-room demonstrations and experiments are supplemented by individual laboratory work on the part of the student, this being recognized as essential to his best interests. Since the work of instruction is thus divided between the lecture hall and the laboratory, an attempt has been made to combine in this book: (1) The principles of electricity upon which the practical applications of to-day depend; (2) the experimental demonstration of these principles; (3) the elements of the arithmetic of electricity used in making practical electrical measurements and calculations.

Illustrations have been generously introduced to make the principles clear, in preference to pictures of electrical machinery in common use, these being supplemented by numbered experiments, which may be conducted with simple and inexpensive, yet efficient, apparatus such as

that described, which was designed for and is now used by the Institute.

A knowledge of fractions, decimals and simple proportion will enable the student to make nearly all the calculations, but if deficient in these subjects, he is advised to study the same in connection with this part of the book.

The numbered formulæ used throughout the text are simple expressions for the accompanying rules; the derivation of each being explained and illustrated by a practical problem completely solved, with each step indicated by the proper formula.

Questions at the end of each lesson are introduced as a special home-work feature, and numerical unsolved problems, with answers, are also given at the end of many of the lessons for the same purpose.

A number of reference tables of useful information and experimental data have been inserted.

In the Appendix will be found a summary and index of the formulæ explained and used in the book, also some mensuration formulæ.

Permission for the reproduction of some cuts from Professor Jamieson's "Elementary Electricity" has been kindly granted by the publishers.

Prepared from necessity, rather than from any desire to increase the copious number of books on the subject, it is hoped that this volume will achieve the desired object and assist other collaborators in the same field.

In view of the cordial reception and wide popularity of the work, and in recognition of the fact that great advances have been made in electrical engineering since the original publication, it has been deemed wise by the successor of the late Prof. C. W. Swoope, to thoroughly revise and bring the book up to date. With this end in view, the standard symbol, I, for current, has been substituted for C, in all formulæ. A number of paragraphs throughout the book, and some Tables have been revised or re-written, while Lesson XXX treating on Electric Lighting has been re-written and enlarged. This labor has been successfully accomplished by his successor at the Spring Garden Institute, Mr. Harry N. Stillman, Assoc. Mem. A. I. E. E., author of Lesson XXXI on Alternating Currents.

PHILADELPHIA, October, 1913.

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LESSON I.

MAGNETISM.

Natural Magnets—Artificial Magnets—Definition of a Magnet—The Poles—Magnetic Attraction and Repulsion—Two Kinds of Magnetic Force—The two Poles Inseparable—Magnetic Substances—Magnetisable Metals—Classification of Magnets—Questions.

1. Natural Magnets.—The name magnet was first applied by the ancients to brown-colored stones, known as magnetic oxide of iron (Fe_3O_4) because these, as taken from the earth, possessed the peculiar property of attracting small pieces of iron or steel. Later the Chinese discovered that if a piece of the ore were freely suspended by a string it possessed the important property of pointing always in a particular direction, nearly north and south; hence they gave it the name of *lodestone* (meaning leading stone), and used it in this manner to navigate their ships. Excellent iron is made from magnetic oxide of iron which is found in the United States (Arkansas) and various other parts of the world. In studying the magnetic attractive force of a piece of lodestone by means of iron filings, it will be found that the attraction for the filings seems to be centered at two or more points on the stone, while at other points no filings are attracted.

Fig. 1.—Natural Magnet Attracting Iron Filings.

Fig. 2.—Magnetised Steel Bar Attracting Iron Filings.

2. Artificial Magnets.—The natural magnet possesses yet a third important property, namely, that of imparting all of its properties to

a piece of hard iron or steel when they are rubbed together without apparently losing any of its original force. This steel (a piece of clock spring or a knitting needle will answer) will now attract filings, when freely suspended come to rest in a northerly and southerly direction, and can be used to magnetise another piece of steel.

Strong artificial magnets are not made from the lodestone, as its magnetic force is not strong, but by better methods to be mentioned later. Figs. 1 and 2 illustrate a natural and artificial steel magnet attracting filings.

3. Definition of a Magnet.—Given two pieces of similar steel, one of which is a magnet and the other not magnetised, how would you determine the magnet? Plunge each piece of steel into iron filings; only the magnetised bar will attract them. Suspend each specimen separately in a stirrup fastened to the end of an untwisted thread, the magnet will come to rest pointing nearly north and south. When turned from this position it again assumes it, while the piece of unmagnetised steel, when so suspended, will rest indifferently in any position. As a third test, the magnetised piece of steel can impart its power to another piece of steel. From these tests then we can define a *magnet as a piece of steel, or other magnetised substance, which possesses the properties of attracting other pieces of steel or iron, or magnetisable bodies to it, and of pointing, when freely suspended in a horizontal position, toward the north pole of the earth.*

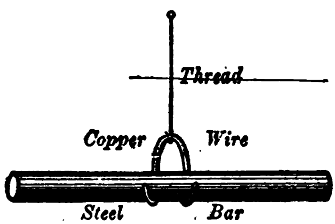


Fig. 3.—Testing a Magnet.

4. The Poles.—The ends of a magnet are termed its poles. The end which points toward the north geographical pole is generally called the North pole, and is usually marked on that end of the magnet by an **N**, or a line cut in the steel, while the other unmarked end is the South (**S**) pole.

By the term *polarity* we mean the nature of the magnetism at a particular point; that is, whether it is **N** or **S**-seeking magnetism.

5. Magnetic Attraction and Repulsion.—Suspend a bar magnet in a stirrup, as in Fig. 3, ascertain and mark its

N-pole and then bring near it the N-seeking pole of another bar magnet held in your hand. The N-end of the suspended magnet is repelled by the N-end of the magnet in your hand

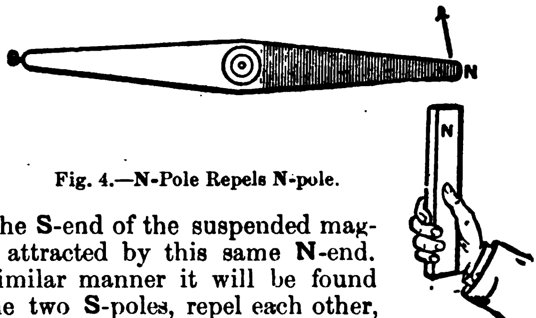


Fig. 4.—N-Pole Repels N-pole.

while the S-end of the suspended magnet is attracted by this same N-end. In a similar manner it will be found that the two S-poles, repel each other, while either S-pole attracts the unlike, or N-pole. Repeat the above experiments with two pieces of magnetite, first ascertaining their N and S-seeking points. The N-seeking pole of one piece repels a like, or N-pole, of the other piece, but attracts a S-pole; thus, *Like poles repel each other but unlike poles attract each other.*

The same experiment can be made with a piece of magnetite and a bar magnet. If the poles of two bar magnets, one held in each hand, be plunged into iron filings and then the N-poles approached to each other, the magnetic force of repulsion will be clearly noted by the repellent action of the

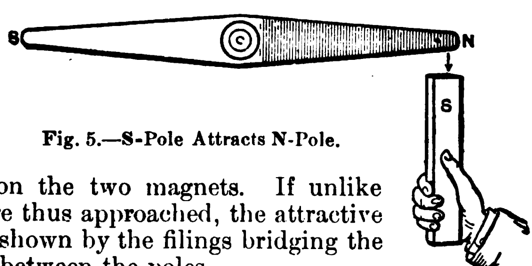


Fig. 5.—S-Pole Attracts N-Pole.

filings on the two magnets. If unlike poles are thus approached, the attractive force is shown by the filings bridging the air gap between the poles.

6. Two Kinds of Magnetic Force.—The above experiments would indicate two kinds of magnetism, or two kinds of magnetic poles, which attract or repel each other, one pole tending to move toward the geograph

ical **N**-pole, and the other pole, toward the geographical **S**-pole. Since we have called the **N**-pointing, or marked pole, the **N**-pole, and have shown that like poles repel each other, then the magnetism of the earth near the **N**-geographical pole must be of the opposite kind, or **S**-magnetism, since unlike poles attract each other. The true **N**-magnetic pole of the earth's magnetism is considered in ¶ 48.

7. The Two Poles Inseparable.—If a piece of steel be rubbed with only one pole of a magnet it will have a **N** and **S**-pole. Upon breaking it into two equal pieces each piece will have a **N** and **S**-pole. It is impossible to produce a magnet with only one pole. A steel bar may have more than two poles, ¶ 40, but always, at least, two opposite poles.

8. Magnetic Substances.—There is a distinction between magnets and magnetic substances. A magnet attracts only at its poles, each of which possesses opposite properties. A piece of iron will attract a magnet, no matter what part of it is approached to the magnet; it does not possess fixed poles or a neutral point, while a magnet has at least two poles, one of which always repels one pole of another magnet.

9. Magnetisable Metals.—The *magnetic metals* used in practice are *steel* and *iron*. Beside these, the metals nickel, cobalt, chromium, and cerium are attracted by a magnet, but only very feebly. Nickel and cobalt are the best of this class, but are very inferior to iron or steel. For practical purposes all other substances such as copper, lead, gold, platinum, wood, rubber, glass, etc., may be regarded as unmagnetisable, or *non-magnetic* substances. Magnetic attraction or repulsion will, however, take place through these substances.

10. Classification of Magnets.—

Magnets. { Natural—The lodestone.
Artificial—Steel rubbed with lodestone.

Artificial Magnets. { Permanent—Steel bar magnet.
Temporary { Iron under the influence of a permanent steel magnet.
Electromagnet—Iron magnetised by an electric current.

QUESTIONS.

1. What is a natural magnet?
2. What three important properties does it possess?
3. How would you locate the poles on a natural magnet?

4. Distinguish between a natural and an artificial magnet.

5. You are given two similar bars of steel, only one of which is magnetised. What tests would you apply to determine which one is magnetised?

6. Define a magnet.

7. State the law regarding magnetic attractions and repulsions.

8. How would you prove that a magnet must always have at least two poles?

9. What is the difference between a magnet and a magnetic substance?

10. Describe how you would magnetise a sewing needle with a piece of lodestone.

11. What do you mean by polarity?

12. A bar magnet is floated on a cork, the **N**-end is toward the observer. What occurs when a **S**-pole is approached to the **S**-end of the floating magnet? What effect when the **N**-end is approached to this same end?

13. What is the difference between a permanent and a temporary magnet? Give an example of each class.

14. You are given a hard steel bar with a notch filed at one end. How would you magnetise it by using the **N**-pole of a magnet so that the notched end would have a **N**-pole?

15. A number of steel needles are inserted vertically into an equal number of corks which are then floated in a jar of water with the eyes of the needles upwards. How will the needles behave when the **N**-pole of a bar magnet is approached to them?

16. Suppose that the eyes of the needles in question 15 are of **S**-polarity, how will they act when the **S**-pole of a magnet is approached to them?

17. What two tests would you apply to prove that although a piece of iron attracts the **N**-pole of a suspended bar magnet yet it is not itself a magnet?

18. Give a general classification of magnets, citing an example to illustrate each class.

LESSON II.

MAGNETISATION.

To Make an Artificial Magnet—Magnetising Each Half Separately—Magnetisation by Divided Stroke—Magnetisation by an Electric Current—Magnetisation by an Electromagnet—Making Permanent Steel Magnets—Compound or Laminated Magnets—Horseshoe Magnets—Horizontal Magnetic Needle—Magnetic Dip Needle—Questions.

11. To Make an Artificial Magnet.—Secure a piece of hard-tempered steel (about 6″ x ½″ x ¼″) and mark one end with a file, which will be the **N**-pole. Place the steel on a table and, beginning at the unmarked end of the steel bar, stroke its entire length with the south end of a strong artificial magnet. Lift the magnet clear at the end and return again for a second stroke in the direction of the dotted line and arrows in Fig. 6. Stroke it about ten times in this manner and then repeat a similar stroking process on the other three sides of the bar. Plunge the newly made steel magnet into filings or small tacks, and note the distribution of magnetism. Suspend it horizontally in the stirrup and observe whether the marked end points toward the north when it comes to rest. Note that the **N**-pole in the magnet you have made was always touched last by the **S**-pole of the magnetising magnet. One pole always induces the opposite pole in any magnetisable body at the point which was touched last by the **S**-pole of the magnet. One pole always induces the opposite pole in any magnetisable body at the point where the pole last leaves that body. ¶ 36.

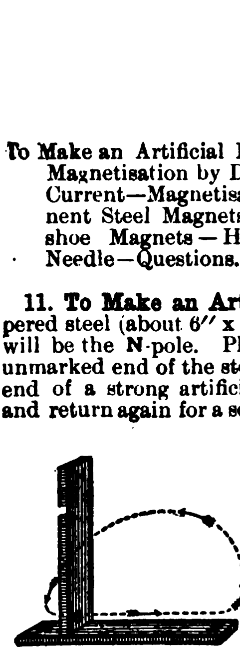


Fig. 6.—Single Stroke.

12. Magnetising Each Half Separately.—A better magnet will be obtained by magnetising each half separately, as illustrated in Fig. 7. Stroke one-half of the steel bar with the **S**-pole, beginning at the centre and following the direction of the dotted line. Repeat this a number of times on each side; then using the **N**-pole, stroke the other half in the same way. A horseshoe-shaped magnet can be used to magnetise another piece of steel by stroking in the direction

of the arrows, as in Fig. 8. In stroking the opposite side, the same limb of the horseshoe must be brought into contact

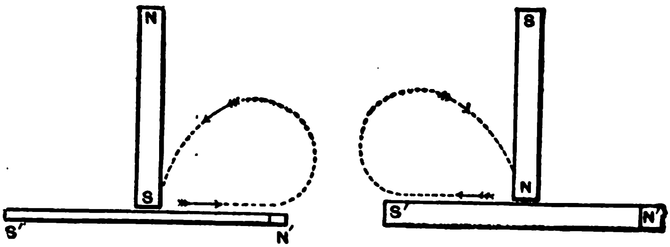


Fig. 7.—Magnetising Each Half Separately.

with the same pole, as before. A piece of soft iron laid across the ends of the horseshoe while being magnetised will give better results.

13. Magnetisation by Divided Stroke.—Place the steel bar to be magnetised on two other bar magnets, as shown in Fig. 9. Take two additional magnets, one in each hand, with the polarities indicated, and proceeding from the centre, with unlike poles, stroke towards the ends in the direction of the dotted lines. Turn the bar over and repeat the operation about ten times on each side.

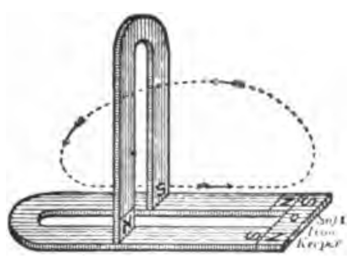


Fig. 8.—Magnetising a Horseshoe Magnet.

14. Magnetisation by an Electric Current.—If a number of turns of insulated wire be wrapped around the steel bar

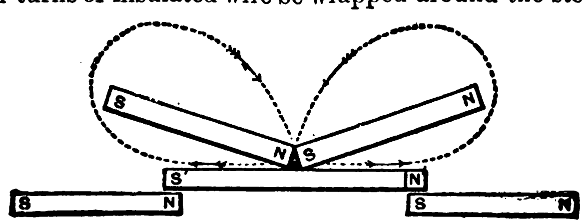


Fig. 9.—Magnetisation by Divided Stroke.

to be magnetised, and a strong current of electricity passed through the coil from a battery or dynamo, as in Fig. 10, the steel will be permanently magnetised with a **N** and **S**-pole, after the current is turned off. Tapping the end of the steel with a hammer, while it is under the influence of the current, will produce better results. Instead of winding the wire around the bar, the bar can be inserted in a spool containing many turns of insulated wire (such as EM, Fig. 11, which can be slipped off of its iron core) when a stronger magnet will

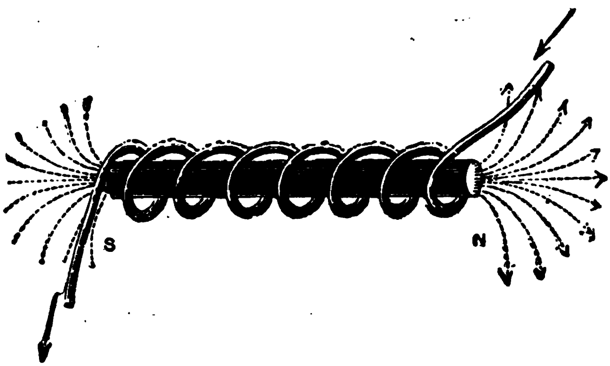


Fig. 10.—Magnetisation by an Electric Current.

be obtained. In making a horseshoe magnet by this method insert one limb all the way in the spool; turn on the current; tap it; turn off the current; remove this limb, and insert the other limb in the opposite end of the coil and repeat the operations. You will now have a magnet, the strength of which, until the saturation point of the steel is reached, will depend on the current strength, and the number of turns of wire on the spool.

15. Magnetisation by an Electromagnet.—A bar electromagnet (i. e., the above spool and its iron core) may be substituted for the permanent steel magnets used in the previous methods for making a magnet, or two bar electromagnets connected by a piece of soft iron forming a horseshoe electromagnet may be used (see Fig. 11.) In this case the current is passed through one spool in one direction, and then through the otner spool in the opposite direction, when the

free ends of the core will have a **N** and **S**-pole. One-half of the bar to be magnetised can now be stroked over one pole

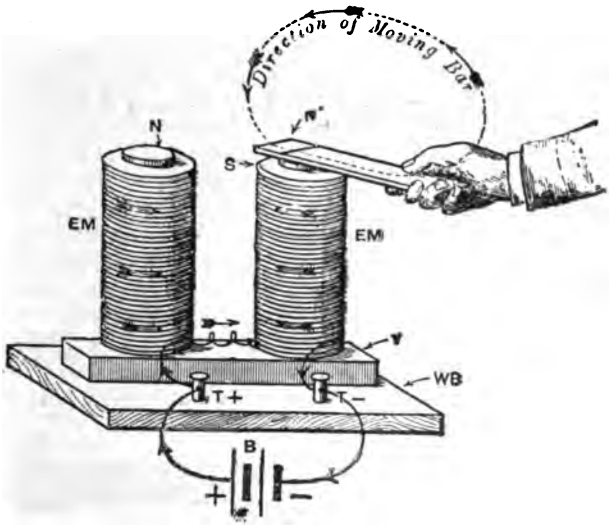


Fig. 11.—Magnetisation by an Electromagnet.

beginning at its middle point and following the direction of the dotted lines in Fig. 11, stroke on all sides, and then stroke the other half of the bar on the other pole.

16. Making Permanent Steel Magnets.—The artificial magnets in paragraphs 2 and 11 are called permanent magnets because they retain their magnetism permanently, to a certain extent, after magnetisation. Some qualities of steel which possess good machine tool properties are not adapted

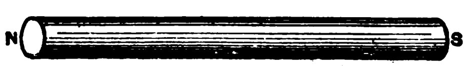


Fig. 12.—Round Bar Magnet.

to making good permanent magnets. Steel containing a certain percentage of manganese cannot be magnetised, while some brands of cast steel, spring steel, and mild plate steel are readily magnetised, but do not retain their magnetism

permanently. Jessop's steel is well adapted to making good permanent magnets. Select a piece of good, close-grained, rolled steel that has not been heated since it was made and cut it (about $6'' \times \frac{1}{4}'' \times \frac{1}{4}''$ or $12'' \times 1'' \times \frac{3}{16}''$). Temper the steel glass-hard by heating it to a moderately bright red temperature and then plunging edgewise into water or oil. It will become very brittle and can be magnetised by any of the methods hereafter given. A permanent magnet will have its strength materially weakened if subjected to shocks or blows, a high temperature, or brought carelessly into contact with the poles of other strong magnets.

Fig. 13.—Student's Bar Magnet Set.

17. Compound or Laminated Magnets.—If a thick piece of steel be magnetised and then placed in an acid bath (such as nitric acid) for some time, whereby the outer surface is eaten off, and then tested for magnetic qualities, it will be found to be almost entirely demagnetised. From this experiment it is inferred that the magnetism has only penetrated the surface of the steel. If a permanent magnet then be made up of a number of thin pieces of steel. magnetised separately, and fastened together with like poles at the same end, it will be stronger than one of solid steel of the same dimensions, because it is more thoroughly magnetised. Such magnets can be made in any form and are known as *compound* or *laminated* magnets.

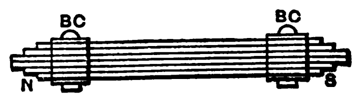


Fig. 14.—Compound Bar Magnet.

18. Horseshoe Magnets.—When a straight bar of steel is bent into the form of a horseshoe, and then properly magnet-

Fig. 15.—Compound Magnet with Soft Iron Pole Pieces.

ised, the end of one limb will be a **N**-pole and the other a **S**-pole. By bringing the poles close together in this manner, the magnet will lift or attract much more than the sum of

the attractive forces when used separately; because, in a bar magnet only one pole could be used at a time, while now both poles act together. A piece of soft iron, called the "*keeper*," is placed across the ends of the poles when they are not in use, to assist in preventing the loss of magnetism. Fig. 16 illustrates a horseshoe magnet of rectangular cross section with its keeper attached. Fig. 13 illustrates the proper method of putting away two bar magnets with their keepers, to prevent loss of magnetism; the unlike poles are placed at the same end, with the keeper connecting them. A laminated, or compound horseshoe magnet, built up of a number of separate horseshoes and fastened together with their like poles at the same end, is depicted in Fig. 17. Laminated horseshoe magnets are used in electrical measuring instruments, magneto-electric generators, and in telephones.

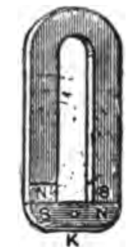


Fig. 16.—Horseshoe Magnet and Keeper.

19. Horizontal Magnetic Needle.—The magnetic needle with its stand is shown in Fig. 18. It consists of a thin

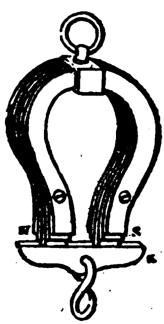


Fig. 17.—Compound Horseshoe Magnet With Keeper.

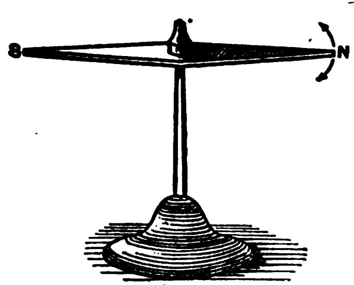


Fig. 18.—Horizontal Magnetic Needle.

piece of magnetised steel in the form of an elongated lozenge, in the centre of which a hole has been drilled, and a glass, agate, or brass V-shaped jewel affixed, so that the needle

will swing freely when poised on a hardened steel point The needle takes up a position **N** and **S** when at rest similar to the suspended bar magnet. Sometimes the needle is suspended from a vertical support by a cocoon silk fibre, in which case it is much more sensitive, due to the elimination of the friction in the poised form. Both types are much used commercially in electrical detecting and measuring instruments, as in the mariner's compass, galvanometers, etc.

20. Magnetic Dip Needle.—This needle is made in the form of a lozenge, similar to the horizontal needle, but it is poised or suspended by means of a shaft running through the

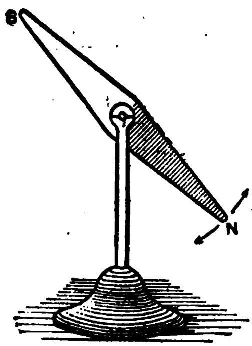


Fig. 19.—Magnetic Dip Needle.

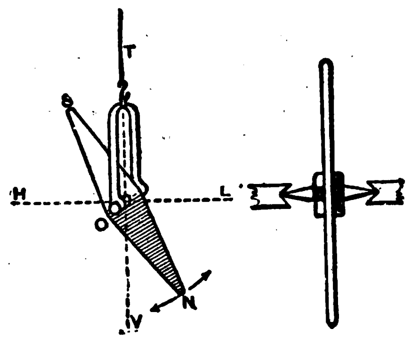


Fig. 20.—Magnetic Dip Needle.

centre of the lozenge at right angles to it, and is held in position by brass V centres, or agate bearings, as shown in Figs. 19 and 20. It is thus free to turn vertically. In some types the cradle holding the horizontal shaft is poised on a steel needle, or swung by fibre suspension. The needle is thus free to take up a position **N** and **S**, and to incline on its axis. The principle and use of the dipping needle is explained in ¶ 52.

QUESTIONS.

1. How would you magnetise a steel sewing needle by the method of magnetising each half separately, so that the eye would be a **N**-pole? Give sketch.

2. How would you magnetise a steel horseshoe magnet by the

"Divided Stroke Method" so that the marked end would be a N-pole? Give a sketch to illustrate your answer.

3. What is an electromagnet?

4. Given a coil of wire, a battery, and a piece of iron, how would you magnetise the iron? What kind of a magnet would it be after the circuit was disconnected?

5. How would you magnetise a steel horseshoe by an electromagnet? Suppose you only had a coil of wire connected to a battery, now then would you proceed?

6. What kind of steel would you select to make a good, permanent magnet?

7. What care is necessary in handling permanent magnets?

8. What is a compound magnet? How would you put four horse shoe magnets together to make a compound magnet?

9. What is the advantage of laminated magnets over those made from solid steel?

10. Describe a horizontal magnetic needle. For what purpose is it used?

11. What is a dip needle? How does it differ from a horizontal needle?

12. Show by a sketch how three bar magnets should be put away without keepers, so that they would retain their magnetism.

13. A laminated permanent magnet is constructed of four strong bar magnets but appears to be very weak. What do you suppose the trouble is, and how would you prove the supposition?

14. A piece of hard steel, bent in the form of a U, is to be magnetised so that both ends will have N-polarity. Illustrate by a sketch how you would proceed to magnetise it by the "divided stroke" method, using four permanent magnets, and indicate all the polarities.

15. How would you magnetise a steel pen, using a horseshoe magnet, so that the point would be a N-pole? Give two tests you would make to prove that you had magnetised it correctly. Make sketch.

LESSON III.

MAGNETIC FIELDS.

Magnetic Force—Magnetic Lines of Force—The Magnetic Field—Making Magnetic Fields—Axis and Equator of Bar Magnet—Questions.

21. **Magnetic Force**—The force exerted by one magnet on another, to attract or repel it, or to attract iron filings, or pieces of iron, is termed magnetic force. It is not perceptible to any of the senses. When the magnet has been plunged into filings, the space thus occupied is shown to be permeated with the force, and the filings serve as a useful indicator to show the nature of the force and its direction and distribution in the space surrounding the magnet. The magnetic force is not the same at all distances, but decreases as the distance from the magnet increases. The attractive force between a magnet and a piece of soft iron is mutual, that is, the iron attracts the magnet just as much as the magnet attracts the iron. This may be illustrated by suspending a piece of iron in a stirrup, as in Fig. 3, and noting the distance at which it is attracted by a magnet, and then suspending the magnet and permitting the iron to occupy the previous position of the magnet; or the magnet may be floated on a cork in a jar of water, and it will be equally attracted by the piece of iron.

22. **Magnetic Lines of Force.**—The magnetic force emanates in all directions from a magnet. To ascertain the direction of the force in the space surrounding a magnet, a

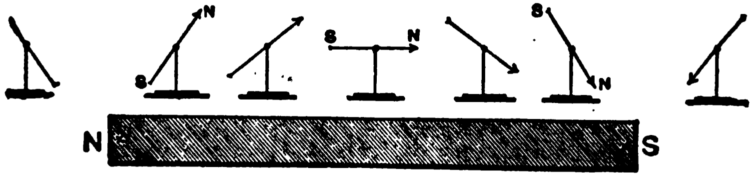


Fig. 21.—Exploring the Magnetic Field with a Dip Needle.

small dipping needle, as in Fig. 21, or a magnetised sewing needle suspended by a thread from its centre, as in Fig. 22, may be used. With the bar magnet flat on the table, place the exploring needle a short distance above the magnet, midway between its two poles. The needle takes up a position parallel to the magnet, with its **N** and **S**-poles attracted by the unlike poles of the magnet, the attractions of the poles being equal. Now move the dipping needle a little to the right of the middle position, and it inclines to the magnet, the angle of inclination increasing as you approach the pole, till it becomes vertical at the pole; if carried past the end of the bar it still inclines to the pole, indicating by its resultant position the direction of the magnetic force at this point. In a similar manner the dipping position underneath the magnet may be noted. Place the magnet on a sheet of paper and make a similar exploration of it with your suspended needle. Mark with a pencil on the paper a dot and X to represent the **N** and **S**-pole of the needle when it comes to rest for each particular position. A line may then be drawn connecting each dot with its X, and the direction of the magnetic force around the magnet will be illustrated graphically in the form of a curve similar to Fig. 23. From these experiments it is deduced that magnetic force is exerted in all directions from a magnet. In similar manner, another series of positions could be taken about one-eighth inch farther distant from the magnet, and another curve indicating the direction of the magnetic force obtained. The entire space surrounding the magnet for a considerable

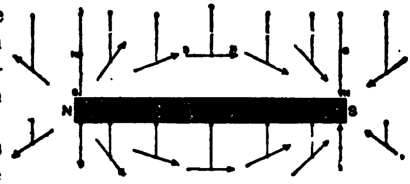


Fig. 22.—Exploring the Magnetic Field.

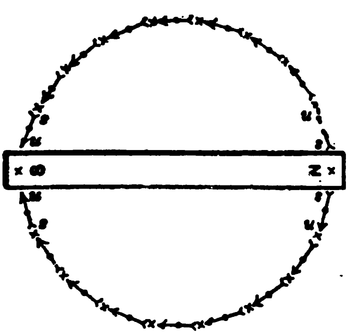


Fig. 23.—Plotting Needle's Position.

distance from it will thus be found to be permeated with magnetic lines of force. Similar explorations made on the other side of the magnet will give the same results.

23. The Magnetic Field.—The space which is permeated by the magnetic lines of force surrounding a magnet is conventionally called the *magnetic field of force*, or simply a magnetic field. It is also assumed that the magnetic lines of force emanate from the **N**-pole of a magnet, pass through the surrounding medium, re-enter the **S**-pole and complete the path, or circuit from the **S**-pole to the **N**-pole, through the magnet itself. Every line or curve of magnetic force must have a complete circuit; hence, as already proven, it is impossible to have a magnet with only one pole. *The magnetic lines complete their circuits independently, and never cut, cross, or merge into each other.* The internal field is much smaller in cross section than the external field, due to the fact that the steel is a much better conductor of magnetic lines of force than the surrounding medium. Because of this concentration of lines of force inside the magnet they are crowded together where they leave the magnet at the **N**-pole, and where they enter at the **S**-pole. The strong attraction at the poles, and none at the middle of the magnet is thus accounted for.

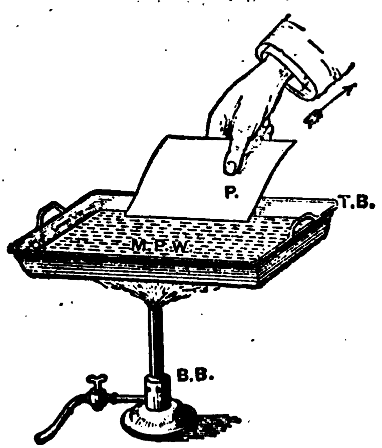


Fig 24.—Coating Paper with Paraffin Wax.

24. Making Magnetic Fields.—Lay a bar magnet flat on a table and cover it with a sheet of cardboard. Obtain some sifted iron filings from which the dust has been removed and enclose them in a pepper-box or piece of gauze netting. Sift the filings over the cardboard, while gently tapping its edge with a lead-pencil. The filings being magnetic bodies, arrange themselves in the direction of the magnetic curves of lines of force and thus produce a graphical

representation of the magnetic field surrounding the magnet, as in Figs. 25 and 26. When it is desired to make a perma-

Fig. 25.—Making Magnetic Field of a Bar Magnet.

nent record of the magnetic field, a piece of paraffin-coated paper is used in place of the cardboard. After the field is

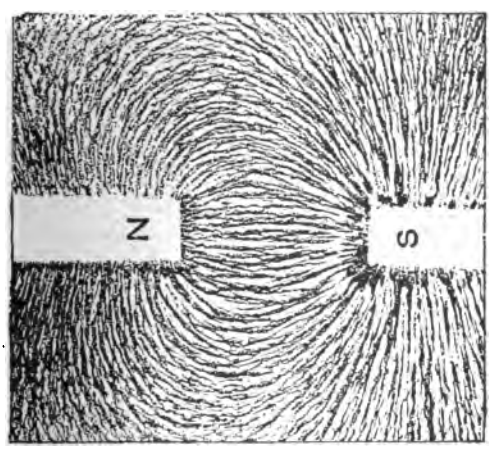


Fig. 26.—Magnetic Field Between Unlike Poles.

produced, the flame of a Bunsen burner is gently applied heating the paraffin, which upon cooling fixes the iron fil-

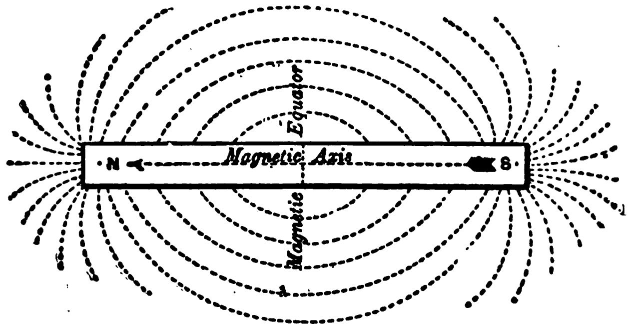


Fig. 27.—Bar Magnet.

ings to the paper. Paraffin paper can be prepared by dipping unglazed paper into a tray of melted paraffin. See Fig. 24. If the field is produced on sensitized photographic paper and then properly exposed to the light, and afterwards developed, permanent graphical records will be obtained. The student should produce all the cases of fields (Figs. 26 to 33), tem-

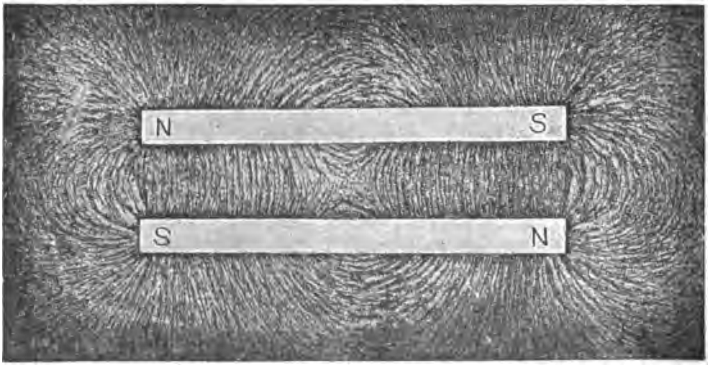


Fig. 28.—Two Parallel Bar Magnets, Unlike Poles Adjacent.

porarily at least, study each one in detail as it is made, and reproduce the same by a sketch at the time it is being made.

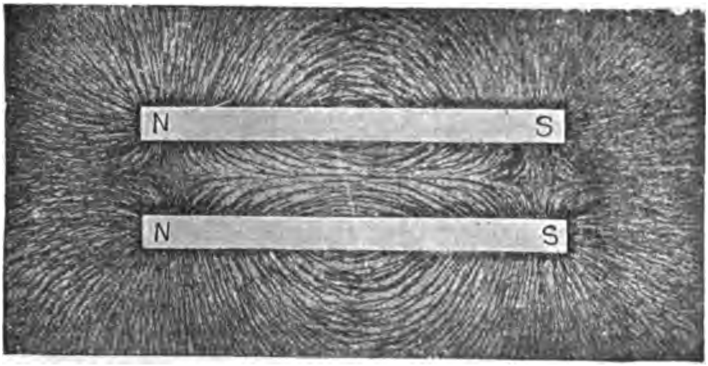


Fig. 29.—Two Parallel Bar Magnets, Like Poles Adjacent.

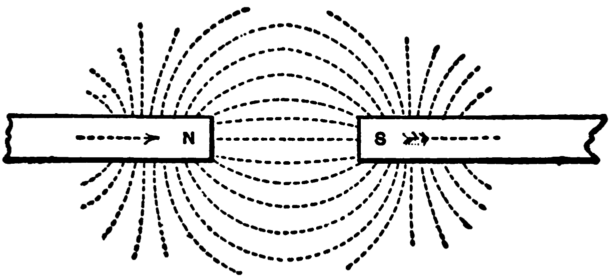


Fig. 30.—Note-book Sketch of Fig. 26.

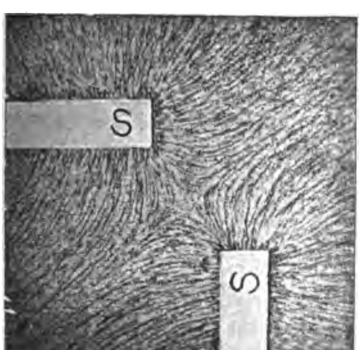


Fig. 31.—Repulsion Between Like Poles.

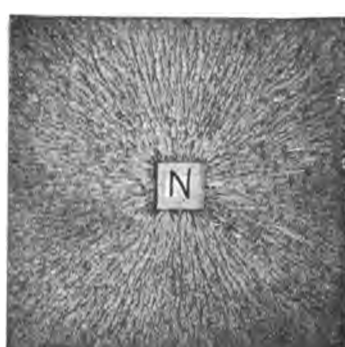


Fig. 32.—Magnetic Field of the End of a Bar Magnet.

Many other possible combinations of magnets to produce these magnetic figures will occur to the student. A thorough knowledge of the direction of lines of force, as depicted by

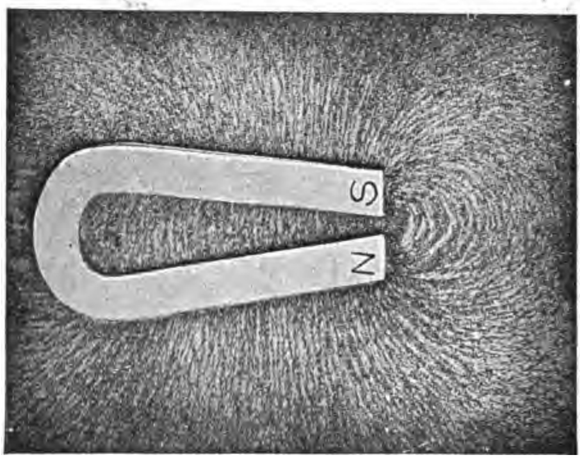


Fig. 33.—Magnetic Field of a Horseshoe Magnet.

the graphical representations of magnetic fields, will greatly assist in the understanding of the phenomena of electro-magnetism and electromagnetic induction, to be considered later.

25. Axis and Equator of Bar Magnet.—The straight line joining the **N** and **S**-poles of a bar magnet is called the magnetic axis (Fig. 27). A line drawn through the neutral point at right angles to the axis is called the magnetic equator. The *neutral point* may be defined as the position midway between the poles where by the aid of iron filings no external magnetism is shown.

QUESTIONS.

1. What is magnetic force? How would you prove its existence and direction around a magnetised steel bar?
2. How would you prove that a piece of iron attracts a magnet just as much as the magnet attracts the iron?
3. Give your idea of magnetic lines of force and state how you

would explore these lines around a bar magnet. Illustrate your answer by a sketch.

4. What is a magnetic field?

5. Describe a process for permanently making magnetic fields.

6. What is meant by internal and external field? Show by a sketch the direction of the lines of force in both.

7. A piece of steel attracts the **N**-pole of a magnet. Would this phenomenon positively prove that the steel is magnetised? Give a reason for your answer.

8. A bar magnet and a horseshoe magnet are laid flat on a table so that their neutral lines form one straight line, **N**-pole opposing **N**-pole. Sketch the graphical field you would expect to see if iron filings were used.

9. Sketch a bar magnet and indicate its axis and magnetic equator.

10. Six horseshoe magnets are arranged symmetrically around the circumference of a circle with their poles pointing toward its centre. The adjacent poles are in the order **NS, SN, NS,** etc. Make a sketch showing the direction of the lines of force as you would expect to see them when iron filings are used.

11. What is meant by the neutral point of a bar magnet?

12. Illustrate by a sketch the neutral point, and, also, the axis and equator of a horseshoe magnet.

13. Two bar magnets with like poles adjacent are laid on a piece of cardboard parallel to each other. A horseshoe magnet is placed so that its poles are directly opposite but a little distance from the bar magnet's poles. Sketch the resultant magnetic field you would expect to see from this combination if iron filings were used.

LESSON IV.

THEORY OF MAGNETISM.

The Nature of Magnetism—Experimental Proof of the Molecular Theory of Magnetism—Breaking a Magnet—Magnetic Saturation—The Magnetic Difference Between Iron and Steel—Retentivity and Residual Magnetism—Destruction of Magnetism by Vibration—Destruction of Magnetism by Heat—Strength of a Magnet—Lifting Power of a Magnet—Questions.

26. The Nature of Magnetism.—What is known as the *molecular theory of magnetism* is offered as an explanation of the phenomenon arising from the magnetism of a piece of steel or iron. The theory, which is beautifully illustrated by

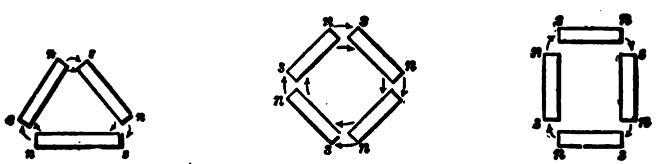


Fig. 34.—Possible Arrangements of Molecules (Magnified).

the experiments following, assumes that in a bar of steel, each of all the individual particles, or molecules which compose it, is a magnet. If the steel or iron is unmagnetised, then the particles arrange themselves promiscuously in the steel, but according to the law of attraction between unlike poles; the magnetic circuits are satisfied internally, and there is no resulting external magnetism. Fig. 34 illustrates (highly magnified) several possible positions, in which the particles in a solid steel bar may arrange themselves, when there is no external magnetism. When the steel bar is stroked with a magnet, or placed in a current-carrying coil of wire, the particles rearrange themselves according to the law of attraction, symmetrically with the axis of the coil, thus breaking up the closed magnetic circuits, and so making

evident external magnetism. An enlarged view of this arrangement of the particles is shown in Fig. 37.

27. Experimental Proof of the Molecular Theory of Magnetism.—Fill a small glass test-tube with coarse steel filings, and insert a cork in the mouth of the tube. Test each end separately for magnetism by bringing it near a suspended needle. Either end attracts the same pole of the needle, proving thereby that it is not magnetised. Treat the tube now as a steel bar, and being careful not to shake it, proceed

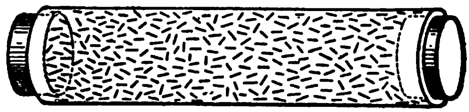


Fig. 35.—Glass Tube of Steel Filings Before Magnetisation.

to magnetise it by any of the methods previously given. Test again with the needle; one end repels one of the needle's poles and attracts the other pole. *Always make a repulsion test to prove that a body is a magnet.* Now shake the tube thoroughly so as to intermingle the filings, repeat the tests above, and you find that the tube is no longer a magnet, but has been demagnetised. The filings are now indiscriminately arranged in the tube with the magnetic circuits of the numerous small magnets completed through each other, Fig.

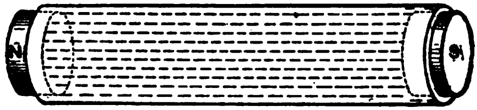


Fig. 36.—Glass Tube of Steel Filings After Magnetisation.

35; hence no external magnetism. When rearranged in the tube under the influence of magnetic force, they assumed symmetrical positions, each one lying in line with, or parallel to its neighbor, **N**-pole next to **S**-pole and so on, Fig. 36. The result of this rearrangement of a number of small magnets would be an accumulation of the lines of force, which, when they reached the end of the tube would have no other path to complete their circuit; so that the tube presents the characteristics of a bar magnet. Fine particles of magnetic

oxide of iron (lodestone) mixed with water may be poured into a tube. When the tube is shaken it is impervious to light, because of the satisfied internal arrangement of the magnetic circuits; when placed in a coil of wire carrying a current the particles rearrange themselves longitudinally so that when viewed from the end of the tube they offer less obstruction to the light.

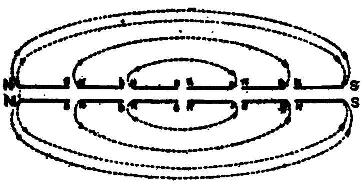


Fig. 37.—Magnified Position of Steel Filings.

28 Breaking a Magnet.—The breaking of a magnet further supports the molecular theory of magnetism. Magnetise a long, thin piece of hard-tempered steel, and mark the **N**-pole. Break it in half and test each piece separately. In one-half the **N**-pole remains **N**, as previously marked, but a

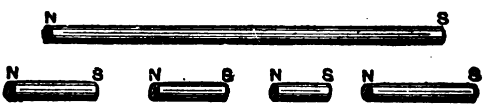


Fig. 38.—Breaking a Steel Magnet.

new **S**-pole is developed, while in the other piece the **S**-pole remains as before and a new **N**-pole is developed. Break these pieces again, Fig. 38, and each part is a perfect magnet, with the poles distributed as in the previous case. Break the

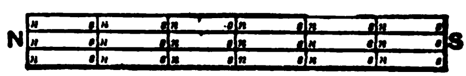


Fig. 39.—Magnified Arrangement of Particles in a Bar Magnet.

remaining pieces until they become too small to be broken, testing each one, and every one is still a magnet. The conclusion is, then, that a steel or iron magnet is an aggregation of small magnets, arranged in the magnified position shown in Fig. 39.

29. Magnetic Saturation.—We cannot see the molecules of iron or steel changing their relative positions under the influence of magnetism, but these experiments are in-

tended to show what probably takes place when steel or iron is magnetised. According to the theory, the magnetised iron or steel has its molecules irregularly disposed, as the steel filings were in the tube when shaken. Magnetisation turns them around on their axes until they are arranged symmetrically. When they have all been turned around the bar is said to be saturated, or completely magnetised; it cannot be further influenced by magnetism, however strong the force.

30. The Magnetic Difference Between Iron and Steel—Retentivity and Residual Magnetism.—Magnetise a bar of steel by insertion in a coil carrying a current of electricity, and then a bar of soft wrought iron of the same dimensions. Test the attractive power of each by nails or filings, while the current is on, and it is found that the soft iron possesses the greater attractive force. When the current is off, the steel possesses far superior attractive properties to the iron, which it retains, for the most part, permanently. The soft iron is magnetised very slightly. The magnetism remaining in the iron is known as *residual magnetism*, and is a most important factor in operating dynamos, since upon it their self-exciting properties depend. The molecules of iron and steel offer some resistance to the force tending to turn them on their axes. The resistance of the steel molecules being much greater, it is difficult to turn them around, but on being once turned around it is equally as difficult for them to turn again to their original position due to the intermolecular friction; hence the resulting permanent magnetism. On the other hand, the molecules of soft iron turn very readily when under the influence of a magnetic force, but assume their original position when the influencing force is removed, as the internal molecular friction is much less, thus accounting for the temporary magnetism in iron. That the particles do not regain their exact original position is shown by the slight trace of magnetism, called residual magnetism, always found in any piece of iron after having been magnetised. The power to retain magnetism is called *retentivity*. The greater the retentivity of a magnetisable body, the more resistance it offers to being magnetised; hence, we see why it is more difficult to magnetise a piece of hard steel than one of soft iron.

31. Destruction of Magnetism by Vibration.—Magnetise a piece of soft iron bar and carefully test its polarity by

the needle. Holding it in the hand, pointing **east and west**, strike the end several blows with a brass or wooden mallet. Upon again testing, you find its qualities as a magnet have been entirely destroyed. You have assisted the few remaining molecules to assume their original position, or you have demagnetised the bar. Slight shocks are sufficient to demagnatise soft iron; steel retains with tenacity the properties of a magnet, but its magnetic strength is impaired by shocks or vibrations; hence, electrical instruments containing permanent steel magnets should be handled with care. *Good bar magnets should not be dropped* on the floor or table. Many practical uses are made of the qualities of soft iron with respect to the ease with which it can be magnetised and demagnetised. Telegraph sounders and the soft iron armature cores in dynamos, are magnetised and demagnetised many hundred times in a minute.

32. Destruction of Magnetism by Heat.—Magnetise a thin strip of steel. Test its polarity. Heat the strip in a Bunsen flame to a bright red color; permit it to cool, and repeat the polarity tests. It is found to be entirely demagnetised. Suspend a small piece of soft iron by a brass chain, heat the iron with a flame, and approach to it a bar magnet. The iron is not attracted until it becomes cool. Heat is a mode of molecular motion; that is, it sets in vibration the particles of the magnetised steel strip, and assists them to satisfy their original internal magnetic condition. On the other hand, it has been found that magnets have their strength increased when subjected to very low temperatures.

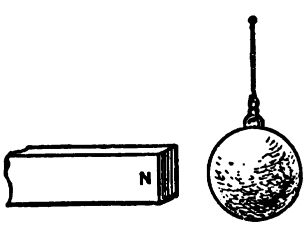


Fig. 40.—Red Hot Iron Ball is Non-Magnetic.

33. Strength of a Magnet.—The strength of a magnet is the amount of free magnetism at the poles, and is not the same as the *lifting power*, which is dependent upon the shape of the poles as well as upon the shape and quality of the body to be lifted. The strength of a magnetic pole is, therefore, measured by its action on another pole at a distance. If one bar magnet repels a magnetic needle, with twice the force of repulsion as that due to another magnet placed at

the same distance from the needle, we would say the strength of the first magnetic pole was twice that of the second magnetic pole. In magnetic measurements a unit strength of pole is adopted by which the strength of any other pole can readily be compared.

34. Lifting Power of a Magnet.—The lifting or portative power of a magnet depends on the strength and form of the magnet. Small magnets lift more in proportion to their weight than large ones. A horseshoe magnet will lift three or four times as much as a bar magnet of equal weight. A long bar magnet will lift more than a short one of equal weight. A magnet with rounded or chamfered ends will lift more than one of the same weight with ends dressed square, even though they are magnetised equally. If a horseshoe magnet has a little weight added to it daily it will be found to attract considerably more than would have been possible if the weight had been originally added. When this weight becomes excessive, so that the armature is detached, the magnet's strength falls to its original value. This growth of the lifting power is a curious and unexplained phenomenon. Electromagnets may be so powerfully magnetised as to require a force of 200 pounds per square inch to separate the keeper from the magnet's poles.

QUESTIONS.

1. Explain what you understand by the molecular theory of magnetism. Give sketches.
2. Sketch several possible positions of the molecules in an unmagnetised piece of steel.
3. What is meant by a magnetically satisfied condition? Give sketch.
4. Sketch the position of iron filings in a test tube before and after it has been magnetised.
5. How would you experimentally prove your idea of the molecular theory of magnetism? Give sketch.
6. A magnet is broken into five pieces. Sketch the pieces and their resultant polarity in the order in which they were broken.
7. Explain how, by successively breaking up a bar magnet, you support the molecular theory of magnetism. Give sketch.
8. According to the molecular theory of magnetism, explain what you mean by magnetic saturation.
9. Why is it that hard steel makes a better permanent magnet than soft iron?
10. What do you understand by retentivity? Give an example to illustrate your answer.

LESSON V.

MAGNETIC INDUCTION.

Magnetic Induction Experiments – Magnetic Induction—Action and Reaction Equal and Opposite—Magnetic Inductive Effect of Like and Unlike Poles—Reversed Polarity—Consequent Poles—Magnetic Screens—Questions.

35. Magnetic Induction Experiments.—(1) Separate a piece of soft iron bar from a magnet by a piece of paper or wood, as in Fig. 41. Plunge the iron into filings; it attracts many more filings while under the influence of the bar magnet than it would do otherwise. It is a temporary magnet made inductively by the influence of a permanent magnet.

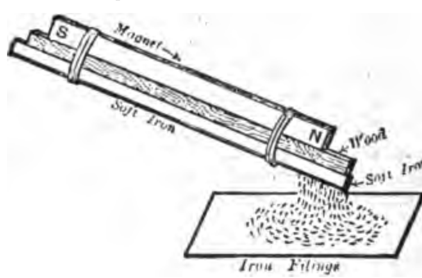


Fig. 41.—Magnetic Induction.

(2) Hold the bar magnet vertically with one end in contact with an end of the iron. Plunge the other end of the iron again into filings. It now attracts more filings than before. Magnetic induction thus takes place between bodies in contact or separated from each other. Interpose between the adjacent ends of the magnet and iron bar pieces of brass, lead, glass, rubber, copper, etc. The filings are attracted to the same degree, when the same distance is maintained, as when these bodies are not interposed.

(3) Support a piece of iron rod about eight inches long, horizontally, in line with, and on the same height, as a poised magnetic needle, when it is pointing toward the **N** and **S**, as in Fig. 42. Leave a small distance between the end of the iron rod and the **N**-pole of the needle. The **N**-pole of the needle induces a **S**-pole in the iron nearest to it, and a **N**-pole at the far end, and is attracted to the bar by the phenomenon of magnetic induction. With the **N**-pole of a bar magnet approach the far end of the iron rod, and the needle is repelled away

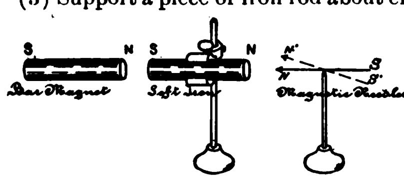


Fig. 42.—Magnetic Induction.

from the iron rod. The bar magnet (the inducing body) being stronger than the needle, induces a S-pole in the end of the iron nearer to it, and a N-pole in the other end ; thus not only neutralizing the needle's inductive effect, but demagnetising the iron, and magnetising it again in the opposite direction. When the magnetising body is removed the needle assumes its former inductive position, provided that the iron is very soft. This experiment proves that the iron has poles when inductively magnetised. To prove that the bar magnet is not repelling the needle, repeat the test without the iron bar interposed and with the magnet at the same distance, when the needle will be only slightly deflected.

(4) The amount of deflection will not be altered in the above experiment when pieces of non-magnetic bodies are interposed. Interpose a text-book while the needle is repelled, and the repulsion is exactly the same as before.

36. Magnetic Induction.—A piece of soft iron, when placed in the magnetic field of another magnet, becomes itself a temporary magnet, having at least two unlike poles, and a neutral point. The iron is the *body under induction*, the magnet the *inducing body*, and the phenomenon known as *magnetic induction.* It may be defined as the action and reaction which occur when the magnetic lines of force, emanating from a magnetic body, make evident the latent magnetism in another magnetic body, either with or without contact between them. Magnetic induction, therefore, takes place when the body is in contact with, or separate from the inducing body. The phenomenon of magnetic induction always precedes the attraction of a magnet for a magnetic body, and takes place through all non-magnetic mediums, whether they are solids, liquids, or gases. One pole induces the opposite pole at that part of the body under induction nearest to the inducing pole, and a like pole at the most remote point. Magnetic induction in iron may be explained by the molecular theory, when it is remembered how readily the molecules of soft iron turn on their axes when subjected to the lines of force of a magnetic field. Each individual iron filing becomes a magnet by induction before it is attracted, and when attracted, acts inductively on its neighbor in the same manner. The methods given in paragraphs 12, 13, 14, etc., for making magnets are based on the principle of magnetic induction, which the student should now apply to each case.

37. Action and Reaction Equal and Opposite.—Bring the end of a piece of unmagnetised steel near to one of the

poles of a poised needle, approaching from an eastern or western direction, as in Fig. 43, the needle is deflected from its original position toward the steel. It induces an unlike pole in the end of the steel nearer to it, and a like pole at the other end. The two unlike poles attract each other. The steel bar tends to move toward the needle, but is not free to move; the needle can and does move. The unmagnetised steel bar thus becomes a magnet before the needle can be attracted to it. A piece of soft iron of the same size and at the same distance, will produce a greater deflection of the needle than the steel, because it is more readily magnetised. Comparative tests can thus be made of the susceptibility of different specimens of iron and steel to the same magnetising influence. There is in all such cases, first, the inductive action of the needle's magnetism on the bar, and then the reaction from this induced magnetism upon the needle, causing it to be deflected. The action being greater upon soft iron than upon steel, the reaction is also greater. In all cases of magnetic induction the action and reaction are equal and opposite. As there is a stronger magnetic field (a greater number of lines of force) near the needle than at a short distance from it, the less the distance between the inducing body and that under induction, the greater will be the inductive action. By placing the bars, one on each side of the same pole of the magnetic needle and at right angles to it and moving the iron bar away until the needle is balanced in a **N** and **S** direction, as in Fig. 44, you can prove by the greater distance of the iron than the steel bar from the needle that the former is more susceptible than the latter to magnetic induction.

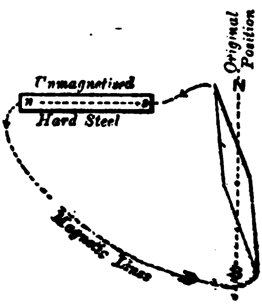


Fig. 43.—Needle Attracted.

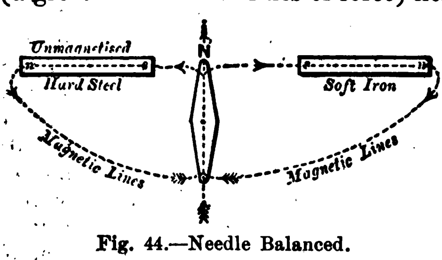
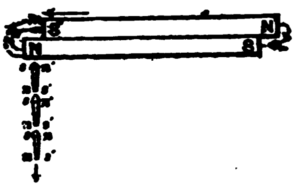
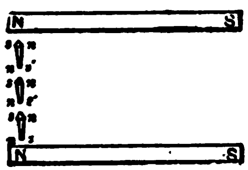


Fig. 44.—Needle Balanced.

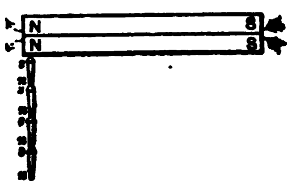
38. Magnetic Inductive Effect of Like and Unlike Poles.—Suspend from a horizontally supported bar magnet three soft iron nails, one below the other, as depicted in the first diagram of Fig. 45. The resulting inductive effects of the bar magnet on the nails is indicated by the polarities marked to the left of the nails. Each nail head has induced in it a S-pole, while all the points are N-poles. Now slide over the top of the bar magnet the *unlike* or S-pole of a similar magnet. The resultant inductive polarities due to this magnet are marked to the right of the nails. This second magnet induces a N-pole at the head of every nail, and a S-pole at every point. The result is a *demagnetising inductive effect* upon the nails, so that their magnetism being neutralized, they drop off by reason of their own weight. The same chain of demagnetising inductive effects will occur if a *like*, or N-pole, is brought up from underneath the suspended nails. (See second diagram.) In the third diagram of Fig. 45 a like, or N-pole, is moved over the top of the magnet, and its inductive effect upon the nails is to reinforce the magnetism already at each nail head and point, so that more nails may now be added. The increased magnetising inductive effect will also be noted if an *unlike* pole is brought up from underneath, as in the last dia-



Demagnetising Inductive Effect of an Unlike Pole.



Demagnetising Inductive Effect of a Like Pole.



Increased Magnetising Inductive Effect of a Like Pole.

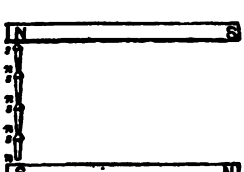


Fig. 45.—Increased Magnetising Inductive Effect of an Unlike Pole.

gram. Two magnets thus placed, with their like poles together, will not support twice as many nails as one magnet, for although they act unitedly upon the nails, they are, in a measure, opposing each other. For this reason also compound magnets are not so strong as the sum of the strengths of the individual magnets of which they are composed.

39. Reversed Polarity.—If two *like* poles of a strong and weak magnet be approached to each other, as a compass needle not free to move and a bar magnet, repulsion will take place up to within a certain distance between the like poles, after which attraction occurs. Then the inductive effect of the stronger magnet has demagnetised the less powerful magnet, and remagnetised it again oppositely, or as we say, reversed its polarity. Magnetic needles often have their polarity thus reversed, so that the marked end points **S** instead of **N**. *In making any tests with a needle always allow it to come to rest first in the earth's field, as the polarity may have been reversed since it was last used.*

40. Consequent Poles.—With a reversal of polarity sometimes more than two poles are manifest in the body having its polarity reversed. In such cases the body will have a number of intermediate poles and neutral points, which may be readily shown by plunging its entire length into iron filings. Such intermediate poles are called *consequent poles* and arrange themselves as shown in Fig. 46. A bar thus magnetised practically consists of several magnets put together end to end, but in the reverse order NS, SN, NS, etc. The nature of each pole can be tested, while it is attracting iron filings, by bringing near it a bar magnet with some filings attracted to it. The attraction or repulsion between the filings can be noticed at a considerable distance.

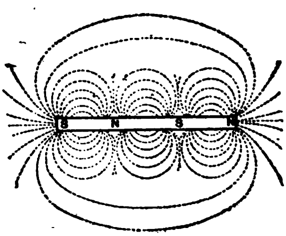


Fig. 46.—Consequent Poles.

41. Magnetic Screens.—Permit a magnet to deflect a magnetic needle from its **N** and **S**-position; the deflection is not altered, if any non-magnetic substance be interposed between the needle and the magnet, such as a piece of wood, glass, or rubber, Fig. 47. The needle's lines of force complete their circuit through the non-magnetic body to the mag-

net, as shown in Fig. 47. A piece of iron, however, when interposed between the magnet and the needle, acts as a *magnetic screen* and reduces the deflection of the needle toward the magnet. A needle, free to move, takes up a position in the earth's magnetic field with its magnetic lines parallel with, and in the same direction as the earth's lines of force. When a magnet is approached to it, it assumes a position which is the resultant of the two forces now acting upon it. No effect is produced by interposing a non-magnetic body, such as a board, but when a piece of iron is interposed part of the lines of force of the magnet (Fig. 48) are now employed in

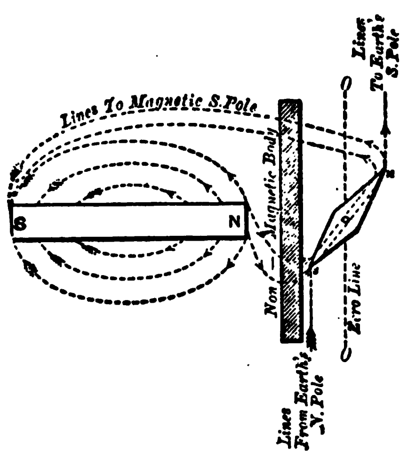


Fig. 47.—Needle Deflected Through Non-Magnetic Body.

magnetising the iron plate by induction. The needle produces a similar effect on the other side of the plate, and being free to move, deflects slightly, until its lines of force are proportionately accommodated between the earth's magnetism and the magnetism of the iron plate. When a thick iron plate is used it forms a perfect shield to the needle against the action of the bar magnet. If a compass needle were placed in the centre of a thick iron sphere it would be entirely screened from any external magnetism. This principle is utilized in the manufacture of heavy cast-iron boxes

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for measuring instruments which are to be placed on switch boards near magnetic fields. Watches are often inclosed in a hunting case made of soft iron to protect their steel main springs from becoming magnetised from any cause. Should

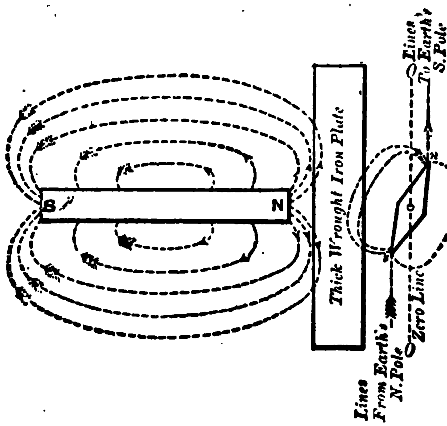


Fig. 48.--Needle Screened from Magnet by a Magnetic Body.

the spring become magnetised the watch generally runs slow, due to the force of attraction between the poles of the spring. Non-magnetic bodies are employed in the springs of non-magnetic watches.

QUESTIONS.

1. Cite and illustrate by sketches an experiment to illustrate the phenomenon of magnetic induction.
2. A bunch of sewing needles is suspended by a thread passing through the eyes, above the N-pole of a bar magnet. State three magnetic phenomena which take place. Give sketches.
3. How do you explain the phenomenon of magnetic induction by the molecular theory?
4. Apply the principle of magnetic induction to a piece of steel you are required to magnetise by rubbing it from one end to the other with one pole of a bar magnet. Give sketches illustrating the stages of magnetisation.
5. A piece of iron and then steel are each held three inches from a poised needle. Which piece will deflect the needle most, and why?
6. Give sketches illustrating four cases of the increased and decreased magnetic inductive effect, of like and unlike poles, of two bar magnets.

7. A magnetic chain of steel pins is formed from one of the poles of a bar magnet. When the chain is removed from the pole it still remains intact. How do you account for this? Give sketch.

8. A chain of soft iron nails is made from the pole of a magnet. Upon attempting to remove the chain all the particles of iron separate from each other. Give sketch and explanation.

9. A compass is supposed to have its polarity reversed. What do you understand by this?

10. How would you correct the reversal of polarity in a compass with two bar magnets so that the arrow head would point N? You cannot get at the needle to stroke it, but there is a stop on the side of the case so that the needle can be held at rest. Give sketch.

11. Upon testing a bar magnet with iron filings it is found to attract filings at the centre and also at each end. How do you account for this? Give sketch to illustrate your answer.

12. A watch is placed in a small pocket-case, which looks like hard rubber, to prevent it from becoming magnetised. What is the case made of, and what is the principle involved?

13. What are consequent poles? Illustrate your answer by a sketch.

14. A bar magnet repels a poised needle 45 degrees, at a distance of 4 inches. An incandescent lamp bulb, containing a vacuum is interposed between needle and magnet. Will the deflection be greater or less? Why?

15. Give several examples of substances that could be interposed in question 14 without disturbing the needle. What are these substances called?

16. A piece of hard steel is interposed in question 15. How is the deflection affected? Give sketch showing the direction of the lines of force between the needle, the steel, and the bar magnet.

17. What is a magnetic screen, and for what purpose is it used?

18. How would you diminish the earth's attractive force on a magnetic needle?

19. A horseshoe magnet is laid flat in a suspended fibre stirrup. What position will it take up when allowed to come to rest in the earth's field?

20. Why is it necessary to harden a piece of steel before it is magnetised?

21. What is residual magnetism, and what is its particular value?

22. State several ways in which you could destroy, or materially weaken the strength of a good permanent magnet. Give reasons for your answer.

23. What care should be exercised in handling instruments containing permanent magnets?

24. A piece of iron is suspended in a stirrup and attracted by the poles of a horseshoe magnet located some little distance underneath it. The N-pole of the bar magnet is approached to one end of the piece of iron, and it is repelled. State the condition of the bar at first and what occurred to cause the repulsion. Give sketches to illustrate the answer.

25. What is your idea of the lifting power of magnets?

LESSON VI.

MAGNETIC CIRCUITS.

Magnetic Circuits—Magnetic Bodies Free to Move—Test for the Distribution of Magnetism—Testing Distribution by a Needle's Oscillation—Pole Pieces, Armatures, and Keepers—Questions.

42. Magnetic Circuits.—A simple magnetic circuit is one composed wholly of a magnetic substance throughout its entire length, and having a uniform cross-sectional area, as, for example, an iron ring, Fig. 178. In a *compound magnetic circuit* the lines of force pass consecutively through several magnetic or non-magnetic substances, as, for example, an iron ring with a section removed, Fig. 178. The lines would then pass from the iron through an air-gap back to the iron again. If the ring were cut into quarters, four air-gaps would be introduced into the magnetic circuit. A *closed magnetic circuit* is one affording a complete magnetic path for the lines of force through magnetic substances, for example, an electromagnet core, the keeper of which is wrought iron, the limbs of steel, and the yoke of cast iron. See ¶ 195.

43. Magnetic Bodies Free to Move.—If a graphical magnetic field be made of a bar magnet and a piece of iron lying in the field, it will be noted that the magnet's field is distorted, and many of the lines pass through the piece of iron. Magnetic lines of force always choose the path of least resistance. If the piece of iron is arranged free to move in the field, it will turn and take up such a position as to accommodate through itself the greatest number of lines of force. If instead of being a magnetic body it is a magnet, it will move, under the influence of the magnetic field in which it is placed, not only so as to accommodate through itself the lines of force of the field, but also in a particular direction, so that its lines will be in the same direction as those of the field. Thus, **N**-lines merge from one point and enter as **S**-lines at another point (Figs. 47 and 48 will serve to illustrate this principle). The fundamental principle in many forms of electrical meas-

uring instruments and electro-mechanical devices is that *a magnetic body, free to move under the influence of a magnetic field, tends to move, so as to accommodate through itself, the greatest number of lines of force of the field.* If the *movable body is a magnet* it moves in a *particular direction* so that its own internal magnetic lines will be in the same direction as those of the field in which it is placed.

44. Test for the Distribution of Magnetism.—According to the molecular theory of magnetism, the relative strength of free magnetism along a bar magnet increases from zero at the centre until it reaches its maximum near the ends, or poles. To prove this, support a long bar magnet horizontally and apply a number of soft iron nails in chains to successive points on the supported magnet. No nails will attach themselves to the magnet at the neutral line, but a gradually increasing number may be suspended until the poles are reached, but beyond the poles not quite so many. See lower half of Fig. 49. In this figure the dotted vertical lines above the magnet have been drawn of such length as to graphically represent the relative quantities of free magnetism at different points on the bar magnet, and the ends of these lines have been joined by a curve which represents to the eye the relative amount of free magnetism at all points on the bar.

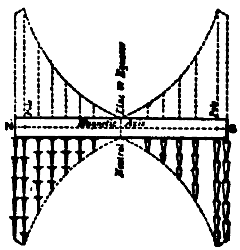


Fig. 49.—Testing Magnetic Distribution by Tacks.

45. Testing Distribution by a Needle's Oscillation.—A bar magnet may be tested for free magnetism by causing a needle to oscillate at successive points near the magnet, from pole to pole. Support the bar magnet vertically, and hold the needle close to the magnet (always at the same distance from the magnet for each position selected); deflect the needle from the position it takes up with reference to the magnet, and then count how many vibrations forward and backward it makes in a given time (one-half minute), which will be the rate of oscillation of the needle. Find how many oscillations are made at other positions equidistant from the magnet in the same time. Move the needle away from the magnet, and ascertain how many oscillations it makes in the same time, when under the influence of the earth's magnetism alone. After making a number of tests, as at the positions shown in Fig. 50, square the number of oscillations for each position, and subtract from each value thus obtained, the square of the oscillations that the needle made in the earth's field. The resulting numbers will be a

series of values representing the quantities of free magnetism along the bar. These numbers may be plotted to scale on lines drawn at right angles to the magnet at points corresponding to the positions selected, as in Fig. 50, and by connecting all the points by a line, a graphical representation of the free magnetism along a bar magnet is obtained. For example, suppose that a magnetic needle makes four to-and-fro swings in one-half minute, under the influence of the earth's magnetism, and seven oscillations in one-half minute, when near the pole of a magnet, then ($7^2 - 4^2$) equals ($49 - 16$) equals 33, so that 33 represents the length of the line to be drawn to any convenient scale at this position of the needle. The following table records the data

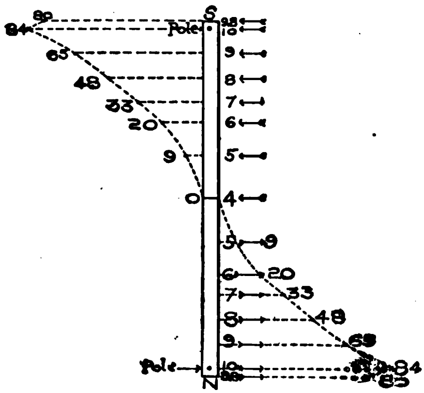


Fig. 50.—Testing Magnetic Distribution by the Needle.

of a needle oscillating test, and Fig. 50 illustrates the plotting of the curve, and also shows the number of oscillations obtained at each position. At the neutral line it will be noted that the oscillations are four, the same number as obtained in the earth's field above:

Table I.—Oscillation Test.

Oscillations.	Oscillations squared.	Oscillations squared minus Earth's Oscillations squared.	Relative Quantities of Free Magnetism.
At centre 4	16	16—16	0
" 5	25	25—16	9
" 6	36	36—16	20
" 7	49	49—16	33
" 8	64	64—16	48
" 9	81	81—16	65
At pole 10	100	100—16	84
" 9.8	96	96—16	80

46. Pole Pieces, Armatures, and Keepers.—To concentrate and direct the magnetic lines of force, which extend in all directions from the poles of a magnet, pole pieces made of iron in a variety of shapes are fastened to the magnet's poles.

Pole pieces of soft iron, Fig. 51, are attached to the ends of the limbs of the magnet and serve to direct or concentrate most of the lines of force between them. In a dynamo these magnetic lines are cut by the rotation of a bundle of wires wrapped upon an iron core, constituting what is known as

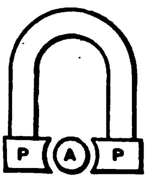


Fig. 51.—Permanent Magnet with Iron Pole Pieces (P) and Armature (A).

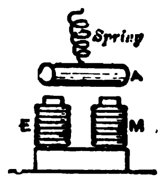


Fig. 52.—Electromagnet with Armature (A).

the armature, represented in Fig. 51 by A. An *armature* is a magnetic body placed between or near, but not touching, the poles of a magnet, and is free to be rotated or moved to and from the poles. A different type of armature from that used in a dynamo is illustrated in Figs. 52 and 53, where a piece of iron is attracted to the poles against the action of a spring. A *keeper* is a piece of soft iron placed across the poles to connect them. Fig. 54. Its function is to provide a complete short circuit, or closed path, for the magnetic lines between two unlike poles.

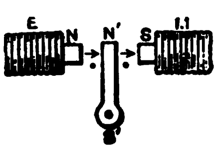


Fig. 53.—Polarized Armature.

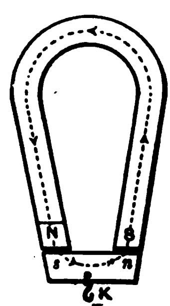


Fig. 54.—Horseshoe Magnet with Keeper.

The magnetism induced in the keeper reacts on the magnet, and not only helps to maintain the strength of the magnet, but also serves to augment it. A magnet deprived of its keeper gradually loses its magnetism. Steel is much more readily demagnetised than magnetised, so that magnets require careful handling when in use and should be provided with keepers when put away.

QUESTIONS.

1. A horseshoe magnet attracts a compass needle. A piece of soft iron is placed across the poles of the magnet and the needle returns to nearly its natural position. Explain this.

2. Explain and illustrate by sketches the difference between a simple, a compound magnetic circuit, and a closed magnetic circuit.

3. How would you magnetise a steel key-ring so that it would have two poles?

4. A steel sphere is attracted by a bar magnet but does not roll toward it. When a soft iron sphere is substituted and placed at the same distance from the same magnet, the attractive force causes it to roll to the magnet. How do you account for this, since the same magnet was used in both cases?

5. How would you put away three bar magnets without keepers so as to preserve their magnetism?

6. Magnetisation always precedes attraction of an unmagnetised body for one that is magnetised. How would you prove this statement in the case of a piece of soft iron attracted by a magnet.

7. A short rod of unmagnetised soft iron is suspended in a stirrup, and placed along the equator of a bar magnet a little distance from it. What position will it take up with reference to the magnet? Give sketch.

8. A short piece of magnetised steel is substituted for the piece of iron in question 7. What position will it take up? Give sketch.

9. Give a concise statement as to the movement of a magnetic body (when free to move), if placed in a magnetic field.

10. A piece of iron is fastened at right angles to a poised magnetic needle at the neutral point so that it extends over each side equally. What effect will it have on the position the needle will take up in the earth's field? Give sketch.

11. A steel magnet is substituted for the piece of iron in question 10. What position will the combination now take up? Give sketch.

12. The following number of oscillations were recorded in a test for distribution of free magnetism of a bar magnet. At the ends 10, then 12, 10, 8, 6, and at the centre 4. The needle oscillated four times in the same length of time when under the influence of the earth's field alone. Find the relative quantities of free magnetism for each position. Plot the points to scale and draw a curve to illustrate the magnetic distribution.

13. Sketch the positions a test needle would occupy when used to explore the field of a horseshoe magnet.

14. How would you magnetise a horseshoe magnet with two bar magnets, so that both ends would have a N-pole and the S-pole located where the neutral point generally is located? Give sketch.

15. The pole of a bar magnet projects over the edge of the table and a piece of iron is attracted to it. Another magnet is brought near the projecting pole and the iron drops off. How do you account for this? Give sketch.

16. You are given a compass needle, and two exactly similar bars, one of iron, the other of steel. How would you distinguish the iron from the steel bar? Give sketch.

LESSON VII.

EARTH'S MAGNETISM.

The Earth's Magnetism—Polarity of the Earth—The Earth's Magnetic Field and Equator—Graphical Field of the Earth's Magnetism—The Magnetic Meridian-Declination—Inclination or Magnetic Dip—Magnetic Maps or Charts—The Mariner's Compass—Magnetisation by the Inductive Effect of the Earth's Field—The Earth's Field Directive, Not Translative—Neutralizing the Earth's Attractive Force for a Needle—Astatic Needles—Questions.

47. The Earth's Magnetism.—Lay a bar magnet flat on the table and hold over it a freely suspended magnetic needle at different positions from pole to pole, as in Fig. 22. At the **N**-pole the needle will be vertical, with its **S**-pole pointing down; when opposite the neutral point, or equator, it will be horizontal; when over the **S**-pole it will be vertical, with its **N**-pole pointing downward. A freely suspended needle carried around the earth from its **N** to its **S**-geographical pole will take up similar positions. At a point near the **N**-geographical pole the needle becomes vertical, with its **N**-pole pointing down; at the earth's equator it is horizontal, and near the **S**-geographical pole it again becomes vertical with its **S**-pole pointing down. The earth may thus be regarded as a huge magnet, with two magnetic poles. Suppose a hole to be drilled through the earth's centre from pole to pole, making an angle of about 20 degrees with its axis, and a bar magnet of somewhat less length than the diameter of the earth to be inserted with its **N**-pole pointing toward the **S**-geographical pole, the resulting distribution of magnetism would be similar to the earth's magnetism.

48. Polarity of the Earth.—We have called the **N**-seeking, or marked pole of a magnet, its **N**-pole, and, as unlike poles attract each other, it will naturally be inferred that the nature of the magnetism near the earth's **N**-geographical pole is **S**-magnetism. The true **S**-magnetic pole is located in the northern hemisphere, while the true **N**-magnetic pole is in the southern hemisphere, Fig. 56. The earth's true mag-

netic **S**-pole is not coincident with its **N**-geographical pole, but about 1400 miles west of it. The **N**-magnetic polar region has not been definitely located.

49. The Earth's Magnetic Field and Equator.—The geographical equator is an imaginary belt passing around the earth midway between its poles. So also, the magnetic equator is an imaginary line encircling the earth midway between its magnetic poles (Fig. 56) and connecting all those points which show no magnetic dip, or where the needle was found to be horizontal (see ¶ 52). This magnetic equator is somewhat irregular in form, owing to the irregular distribution of the earth's magnetism. The lines of force of the earth's magnetic field may be considered to emanate from the true **N**-magnetic pole in the southern hemisphere, and curve around over the surface of the earth, entering again at the true **S**-pole. The lines of force act on a freely suspended magnet in such a manner, that it turns on its axis, until it lies as nearly as possible in the direction of the lines of force, according to the principle enunciated in ¶ 43.

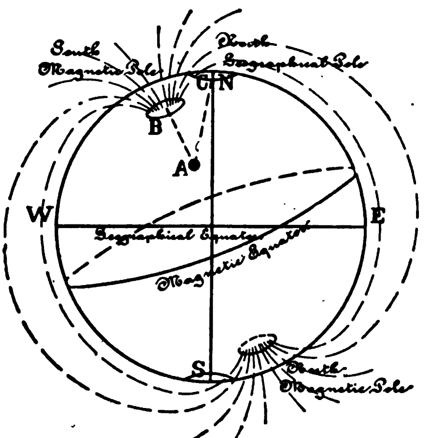


Fig. 56.—The Earth's Magnetic Poles and Equator.

50. Graphical Representation of the Earth's Magnetic Field.—Magnetise a large steel sphere, such as is used in roller bearings, by placing it between the unlike poles of two bar electromagnets so that its diameter and the axis of the magnets form a straight line. When plunged into filings the poles are readily observed. Cut a hole, equal to the diameter of the ball, in a sheet of cardboard and place it over the sphere horizontally so that its plane passes through the axis of the sphere containing the poles. Make a graphical field by the aid of iron filings, as shown in Fig. 58, and you

have a typical representation of the magnetic lines of force surrounding the earth, and called the earth's field.

51. The Magnetic Meridian—Declination.—Just as the geographical meridian is an imaginary line, drawn on the earth's surface in a plane which passes through the geographical poles of the earth and a given place, so, also, the *magnetic meridian* may be regarded as an imaginary line drawn on the earth in a plane which passes through the magnetic poles of the earth and a given place, or a line in the vertical plane containing the axis of a magnetic compass needle at any given place. At most places the geographical and magnetic meridians differ, and the angle between them is known as the *angle of declination* of any given place.

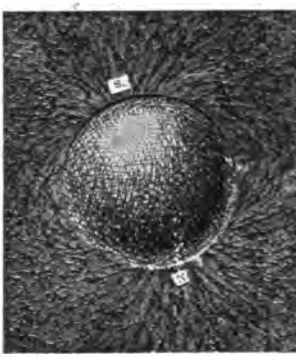


Fig. 58.—Field of a Magnetised Steel Sphere Representing Earth's Field.

It indicates just how far away from the true geographical north the compass needle points. This angle of declination is very slowly, but constantly changing. In New York city in 1905, the declination was 9° 05′ W., which means that when the compass needle comes to rest at this place the true geographical north will be 9° 05′ to the east of the direction the needle points.

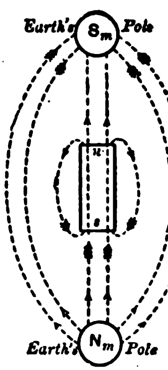


Fig. 59.—The Polarity of the Earth and a Magnet.

Suppose a person to be located at point A, Fig. 56, the direction of true north is along the line AC, while the compass needle at position A points along line AB. The angle between these lines is the angle of declination. In Columbus, Ohio, and Charleston, S. C., in 1900, the declination was zero; that is, the true **N**-pole was just in line with the magnetic pole at these points, or the two meridians coincided. Moving west from point A, Fig. 56, the declination decreases until a locality is found in central Asia where the meridians again coincide.

Places in the Atlantic Ocean, Europe, and Africa, between these lines of no declination, would have a declination west of the true **N**, while at places on the other side of the globe between these lines the needle would point east of the true north. In steering ships at sea by the compass, references are made to a chart, giving the localities corresponding to the different values of the declination of the needle.

52. Inclination or Magnetic Dip.—If a long knitting needle be carefully balanced and suspended by a silk thread, it will assume a horizontal position. When magnetised its **N**-end will point downward, or dip toward the earth's magnetic **S**-pole. This needle being free to move in all directions, takes up a position along the lines of force of the earth's field. The angle which the needle makes with the horizontal is termed the *angle of dip*. The dip needle (see ¶ 20) is horizontal at the magnetic equator, and the angle of dip increases as you go toward either pole, the needle being vertical at the poles. At New York city in 1905, the dip was 72° 2′ N., which means that the knitting needle, or dip needle, as shown in Fig. 19, will take up a position with its axis at 72° 2′ with the horizontal plane with its **N**-end pointing downward, Fig 61.

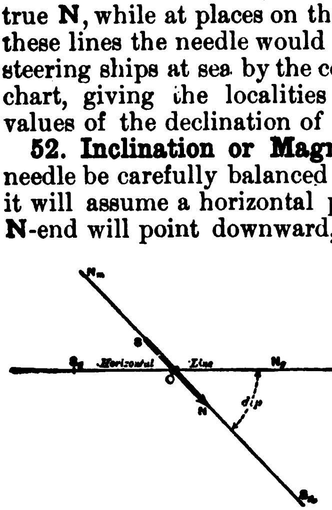


Fig. 61.—Angle of Dip.

53. Magnetic Maps or Charts.—Magnetic maps are prepared, on which the places of equal magnetic dip are connected by lines which run similar to the parallels of latitude, but quite irregular, and are called *isoclinic* lines. Similarly, lines connecting places of equal magnetic declination are called *isogonic* lines. They correspond with the meridians of longitude, but are also irregular. Such maps are prepared from time to time by the United States Geodetic Survey, and are used in determining localities, especially in connection with the mariner's compass on board ships.

54. The Mariner's Compass.—In small pocket compasses the magnetic needle is poised on a jewel bearing, and above a graduated scale, fastened to, or engraved on the containing box. In using this compass, it is first necessary to

permit the needle to come to rest pointing **N** and **S**, and then gently twist the box around until the point marked **N** on the scale, is directly under the **N**-pole of the needle. The true geographical north will then be so many degrees east, or west of the position the needle assumes when pointing to the **N**, or marked position, on the scale. See ¶ 51. In the mariner's compass the needle is fastened to the underside of the cardboard scale, and needle and scale swing around together, the **N**-point on the scale always pointing to the north. When it is desired to steer in any particular course, as northwest, the ship's helm is turned till the northwest on the movable dial is opposite a fixed vertical black line (termed the "lubber line") which is drawn on the inside of the bowl, J4, Fig. 62, in line with the direction of the ship's motion. The compass box is supported on gimbal bearings, so that no matter how much the ship may roll or lurch the card will always be level. The construction and method of support are shown in the sectional view, Fig. 62, and the plan in Fig. 63. Many precautions have to be taken in adjusting a ship's compass, to compensate for several errors likely to arise, caused by the influence on the needle of the hull, or the cargo, or electric light wires in the vicinity, etc.

Fig. 62.—Mariner's Compass.

55. Magnetisation by the Inductive Effect of the Earth's Field.—Procure a soft iron bar about 14 inches long, test it for polarity, and then hold it in one hand in the magnetic meridian, with one end pointing or dipping downward at an angle of about 70 degrees to the horizontal, Fig. 64. Strike the bar several hard blows with a hammer, and then test for polarity. The lower end will be found to possess a **N**-seeking pole, and the upper end a **S**-seeking pole. Reverse the bar, after first demagnetising it by blows while held in an east and west direction, and the lower end is again

magnetised and becomes **N**-seeking. The earth's field has induced poles in the bar by induction; the hammer blow simply assisting the molecules to turn around according to the molecular theory. In a like manner tests made with a compass needle on iron and steel girders in buildings under construction, will show that the bodies have been magnetised by the inductive action of the earth's field. It seems probable that the natural magnet, or lodestone, is due to the earth's magnetic inductive action.

Fig. 63.—Plan of Compass Card and Bowls.

INDEX TO FIGS. 62 AND 63.

CB represents Compass Bowl and Card.
J_1J_2 represents Compass Bowl Journals.
GR represents Gimbal Ring.
J_3J_4 represents Gimbal Ring Journals.
BB represents Binnacle Bowl.
l represents Lubber Line (Fig. 62.)

56. The Earth's Field Directive, Not Translative.—Float a bar magnet on a cork in a basin of water. The bar takes up a **N** and **S**-position, due to the earth's field, but is not attracted toward the side of the basin nearest to the earth's magnetic **S**-pole, as might be expected, we being so much nearer the south than the north magnetic pole. The poles of the earth are so far away that the short distance between the two poles of the bar ceases to be of any account, when compared with the distance of these poles from the earth's poles. The forces of attraction

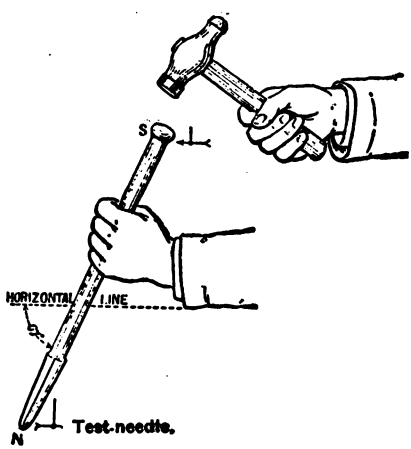


Fig. 64.—Magnetisation by the Earth's Field.

and repulsion on one pole may, therefore, be considered equal and opposite, so that the bar is simply directed, and there is no motion of translation. The distance through which the earth's magnetic pole attracts the **N**-pole of a magnetic needle is less than the distance through which the **S**-pole of the needle is repelled by the earth's **S**-pole. This difference in the distances between the two poles of the earth is so small (equal to the length of the magnet) that the force of attraction is practically no greater than that of repulsion. The needle, therefore, turns in the direction of the two forces, but there is no motion of translation. If the pole of another magnet be approached to the floating magnet, Fig. 65, at such a distance that the length of this magnet is considerable, as compared with the distance between the two magnets, then the floating needle will be both directed and attracted.

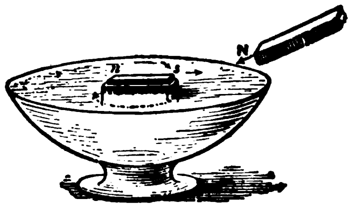


Fig. 65.—The Earth's Force not Translative.

57. Neutralizing the Earth's Attractive Force for a Needle.—Hold above, and parallel to a compass needle, a bar magnet with its **N**-pole pointing in the same direction as

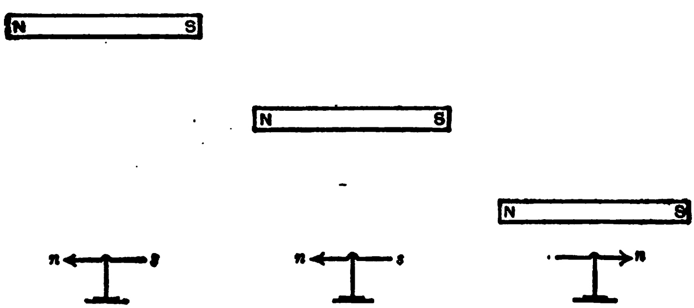


Fig. 66.—Neutralizing the Earth's Attractive Force for a Needle.

the needle's **N**-pole, Fig. 66. If the height of the bar is considerable, the needle is not appreciably affected. Slowly lower the magnet, and a point will be found where the needle will be observed to waver. If the magnet be fixed at this

position the needle will stand in any position given to it, showing that the earth's directive attracting force has been *neutralized.* If the bar magnet is further lowered, the needle swings around and takes up the position shown in the right hand diagram of Fig. 66. A bar magnet used to neutralize the earth's field in this manner is used in some galvanometers. (See Fig 163.)

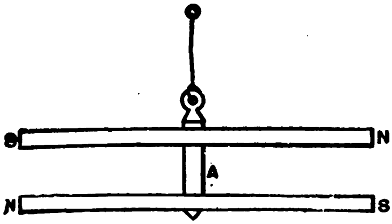


Fig. 67.—Astatic Needle.

58. Astatic Needles.—If two similar bar magnets, equally magnetised, be fixed to a rigid support, one above the other, with unlike poles at the same end, Fig. 67, the system will be independent of the earth's magnetism, and will come to rest in any desired position. When two needles are so arranged they form what is called an *astatic needle.* Astatic means without polarity, and such needles are used in very sensitive galvanometers, Fig. 167.

QUESTIONS.

1. Explain your idea of the earth's magnetism. Make sketch.
2. What is meant by the polarity of the earth's magnetism?
3. How do you account for the fact that the N-pole of a magnet always points N, since like poles repel each other?
4. Sketch the position a test needle will take up if used to explore the earth's field.
5. What is the earth's magnetic equator? Give sketch.
6. What do you understand by the magnetic meridian? Give sketch.
7. Describe and illustrate what is meant by magnetic declination.
8. A long knitting needle is carefully balanced so that when suspended in an east and west position it remains horizontal, but when pointing N and S it acts as if one end had been weighted. How do you account for this? Give sketch.
9. Of what value are magnetic charts and how are they constructed? Give sketch.
10. What do you understand by an inclination of 70° 6′ N?
11. How does the construction of a mariner's compass used on board ship differ from a little magnetic test needle?
12. A soft iron bolt is held in the earth's magnetic meridian at the proper angle of inclination, with the head pointing downward and struck several blows with a hammer. The head is then presented to the N-pole of a compass needle. How does it affect the needle?

LESSON VIII.

VOLTAIC ELECTRICITY.

Electricity—Electrical Effects—Generation of Electric Currents by Chemical Means—A Current of Electricity—Simple Voltaic Cell—Volta's Pile—The Circuit—Conductors and Insulators—Direction of the Current—Poles or Electrodes and Plates—Detector Galvanometer—Potential and Electromotive Force—Chemical Action in a Voltaic Cell—Why the Hydrogen Appears at the Copper Plate—Polarization—Table II–Polarization Test—On What the Electromotive Force of a Cell Depends—Table III–The Electro-chemical Series—Local Action—Amalgamation—Questions.

59. Electricity.—The word electricity has been applied to an invisible agent known to us only by the *effects* which it produces, or various *manifestations*. While the exact nature of electricity is not known the laws governing electrical phenomena are clearly understood and defined, just as the laws of gravitation are known, although we cannot define the nature of gravity. Electricity was assumed, by the early scientists to be a fluid, or several fluids, contained in neutral bodies in equal amounts. When by any means this equality was disturbed in a body, electrical manifestations occurred. Electricity is neither matter nor energy, therefore, it cannot be a fluid, and in the light of later scientific knowledge the fluid theory has been discarded. The theory now generally accepted is, that due to a condition of the *ether*, such as a state of strain or other manifestation in the *ether*, we have the phenomena which we call *Electricity*. The flow of electricity through a wire is analogous to the flow of water through a pipe so that it is said to flow through or around a wire, and the fluid theory is still useful in giving a clear understanding of some of the electrical phenomena.

60. Electrical Effects.—The manifestations produced by electricity may be divided into four distinct classifications for studying the subject. First, *electricity when at rest* is known as *statical electricity* and the bodies electrified are said to be *statically charged;* the term *electrostatics* applies to this subject.

Second, *electricity in motion* differs from statical electricity and is treated as a *current of electricity.* Third, *electricity in motion produces magnetism* which has been termed electro-magnetism. Fourth, when *electricity is vibrated* very rapidly it produces a fourth state, known as *electrical waves.* All these phenomena are very intimately associated with each other, and are due to the one invisible agent, *electricity.* In this book we will limit the study to *currents of electricity* and *electromagnetism*, which form the basis of a great many practical electrical applications.

61. Generation of Electric Currents by Chemical Means.—

Experiment 1: Fill a tumbler two-thirds full of dilute sulphuric acid (one part acid to 20 parts water) and partially immerse in the same a strip of sheet zinc, say one inch wide by five inches long. Bubbles of gas immediately collect on the zinc, and then detaching themselves, rise to the surface of the liquid, being rapidly replaced by other bubbles as the action continues. These bubbles of gas are hydrogen (one of the gases of which water is composed) and when collected, by displacing water in an inverted test tube held over them, this gas may be ignited, and will burn with a pale bluish flame. If the zinc remains in the acid for some time it wastes away or is dissolved in the liquid.

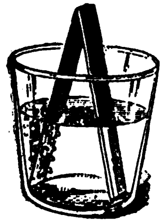


Fig. 69.—Copper and Zinc in Acidulated Water.

Exp. 2: Place a strip of copper, of about the same dimensions, partially in the acid as before. No bubbles of gas are seen rising from the copper. If this metal is allowed to remain for some time it will not apparently be acted upon by the acid.

Exp. 3: Place the strips of copper and zinc in the tumbler of acid, not permitting them to touch each other, inside or out. Hydrogen gas continues to rise from the zinc as before, but there is no action on the copper plate. Bring the outer extremities of the copper and zinc strips into contact, Fig. 69, and torrents of bubbles are *now seen to rise from the copper strip*, in addition to the bubbles rising from the zinc strip. If collected, the gas evolved from the copper proves to be hydrogen, the same as that rising from the zinc. If the action is permitted to continue for some time, upon examination the zinc is found to have wasted away, while the copper remains unchanged. Break the external contact between the plates and the action at the copper instantly ceases, but the zinc wastes away as before.

Exp. 4: Remove the zinc strip from the liquid, and while it is still wet with the acid rub over its surface a little mercury. Upon being replaced in the solution the acid does not attack it. Repeat Exp. 3 with this "amalgamated zinc" (see ¶ 76), and note that now bubbles rise only from the copper plate, when the ends of the two strips are brought together, and that none rise from the zinc plate, but that it is still the zinc plate which wastes away.

Exp. 5: Connect wires of any metal to the copper and zinc plates, being sure that you have bright metallic contacts. Bring the extremities of these two wires together after they have been brightened and hydrogen gas is seen to rise from the copper plate as before, while there is no action at the zinc.

When the wires are separated the action ceases, but commences again as soon as connection is made. Interpose *between* the two connecting wires pieces of glass, mica, rubber, paper, wood, porcelain, etc., or connect the two plates by a bridge made of any of these materials, *no action appears at either plate.*

It thus requires a connection between the two plates to cause chemical action, and this connection must be of a particular kind. It would seem that the plates exert an influence upon each other through the connecting wire. We will now ascertain whether the connecting wire possesses any extraordinary qualities when thus connected with these dissimilar plates.

Exp. 6: Set up a poised magnetic needle pointing **N** and **S.** Bring above and parallel to it a portion of the connecting wire used in the last experiments (as in Fig. 70).

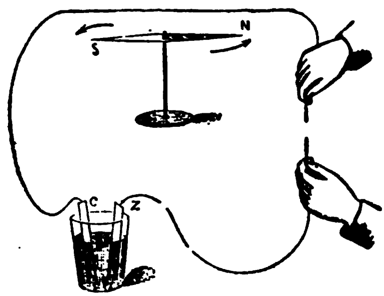


Fig. 70.—Deflection of the Magnetic Needle.

When the ends of the wires are brought together the needle immediately turns upon its axis at right angles, or nearly so, to the wire, after a few vibrations, and remains in this position until the connection is broken, when it assumes its normal position. The deviation of the needle from its original position is termed the *deflection of the needle.* Note that chemical action continued in the tumbler as long as the needle was deflected, and at the expense of the zinc rod.

Exp. 7 With the wire arranged as in Exp. 6, interpose pieces of tin, steel, copper, iron, lead, gold, brass, aluminum, etc., between the connecting wires, and the needle is deflected as before. When pieces of paper, glass, wood, mica, etc., are interposed, however, there is no deflection of the needle, which again proves the necessity of a suitable connector between the copper and zinc plates.

Exp. 8: Test an iron rod by iron filings for magnetism. It does

not attract them. Wind a few turns of cotton-covered wire around the iron rod and plunge it into the filings, after first connecting the ends of the wires to the two plates in the tumbler. Filings are now attracted to the iron core, but drop off when the connection to the plates is broken. This then, is a temporary magnet, produced by the magnetic properties possessed by the wire.

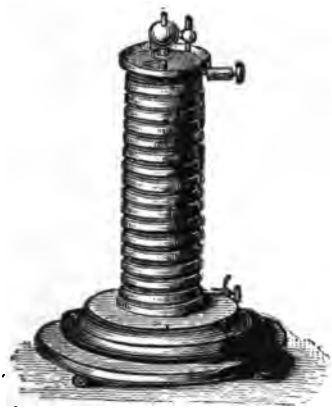
62. A Current of Electricity.—From the foregoing experiments it appears, that when zinc and copper are immersed in an acid solution and connected by a wire, the wire possesses *unusual magnetic properties.* The cause of this magnetic effect, and other effects associated with it to be noted later on is attributed to electricity, and the property possessed by the wire said to be due to a transference of electricity from one plate to the other, the wire acting as a conducting medium. When we speak of a current "flowing through the wire from plate to plate," it is simply a convenient expression used to describe the phenomena involved, although we do not know what actually transpires.

An ebonite or glass rod is *electrified* when rubbed with flannel, silk, etc., and possesses the power of attracting light bodies to it, and also of attracting or repelling another similarly electrified rod, according to the nature of its *electrification.* When the portion of a rod so electrified is touched by the hand, or other conductor, the electrification disappears and the body is said to be discharged. The two plates in the tumbler may be said to be electrified to different degrees of electrification, and when they are connected by a wire, the electrification discharges from the higher to the lower electrified plate. The action of the acid upon one plate more than the other, however, tends to keep the plates at different states of electrification and the successive discharges through the connecting wire become so intensely rapid that they form practically a *continuous current* of electricity.

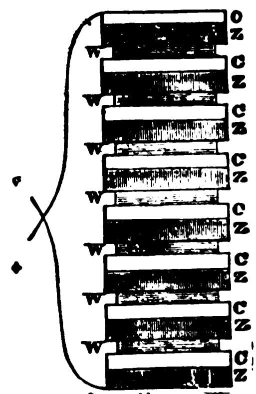
63. Simple Voltaic Cell.—When two *dissimilar* metals are partially immersed in acid solution, which is capable of acting chemically upon one of them more than upon the other, when they are connected by a wire, the combination constitutes a voltaic cell. The name voltaic is derived from an Italian physicist, Volta, who first discovered the cell in 1800. It is sometimes called a galvanic cell, after Volta's contemporary, Galvani. Correctly speaking, the word battery applies to a number of such cells connected together, though

the name is commonly applied to a single cell. The solution in which the metals are immersed is called the electrolyte, or exciting fluid, or excitant.

64. Volta's Pile.—Volta's pile, which is the parent of all batteries, consists of a number of discs of copper (C) and zinc (Z), Fig. 71, with a cloth or blotting paper (W) moistened with salt water and placed between them. When the end discs are connected by wires brought into contact, the same phenomena occur as already described with the Volta cell.



Volta Pile.



Connections of Volta Pile.

Fig. 71.

Volta soon found that better results were obtained by using the two metals immersed in an acid solution, hence our simple voltaic cell.

Fig. 71 also illustrates a Volta pile made for experimental purposes. It is equivalent to a number of Volta cells with the zinc of one cell connected to the copper of the next one, and so on.

65. The Circuit.—Considering again our simple voltaic cell, Fig. 70, the term *circuit* is applied to the *entire path* through which the transference of energy takes place, or the current of electricity is supposed to flow, and the wire joining the plates is called the *conductor*. The circuit then consists of not only the conductor between the plates outside of the cell, but the liquid conductor between the plates inside of the cell; hence we speak of the *internal* circuit and the

external circuit. The *complete circuit* includes the conducting wire, the two plates which act as conductors, and the liquid between them. Bringing the two extremities of the wires into contact is called *making*, or *closing* the circuit, and their separation again, *opening*, or *breaking* the circuit.

66. Conductors and Insulators.—The substances which when interposed between the terminal wires of a voltaic cell do not interfere with the deflection of the magnetic needle (as the metals), are known as *conductors* of electricity, because they allow the current to flow through them, while other substances so interposed, as glass, wood, mica, etc., interfere with the action in the cell and upon the needle, and are therefore called *insulators*. A classified list of conductors and insulators is given in ¶ 125.

67. Direction of the Current.—

Exp. 9: Place the conducting wire of a voltaic cell over and parallel with a magnetic needle when it is pointing **N** and **S**, Fig. 72. Close the circuit and note whether the **N**-pole of the needle points east or west when the current is flowing. Say it is deflected to the east. Now reverse the wire connections at the battery plates (that is, connect the end of wire which was attached to the zinc to the copper, and vice versa), the **N**-pole of the needle now points west if the wire is held as before.

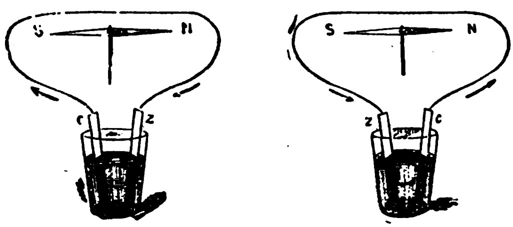


Fig. 72.—Direction of the Current.

This experiment indicates that electricity exists in part, as a magnetic force around a wire, and on account of the behavior of the needle, that this force has direction. For this reason electricians have agreed to assume that the electricity flows from the *copper* terminal *to the zinc* terminal *through the conducting wire*, and from the *zinc plate* to the *copper plate through the solution.*

68. Poles or Electrodes and Plates.—The copper plate is called the *negative plate* or element, and the zinc plate the *positive plate* or element, while the external end of the copper plate or any wire connected thereto is called the *positive pole* or electrode (no connection whatever with magnetic pole), and

the external end of the zinc plate, or wire connected thereto, the *negative pole* or electrode, Fig. 73. If we bring the + (plus sign for the positive) and — (minus sign for negative) wire from a cell together, making the circuit, the current passes from the + (copper) to the — (zinc) terminal across the junction, and also from the + plate (zinc) to the — plate (copper) through the cell. In any electro-generative device that pole is considered *positive from which the current flows*, and that pole *negative to which the current flows*. As Zn, stands for zinc, and negative begins with the letter N, this may aid in remembering the terminals or poles. In any cell the *positive plate* (generally zinc) is the one most acted upon, the current being supposed to start at the surface of this plate, travel through the solution to the copper plate, and from the copper terminal to the zinc terminal through the external circuit.

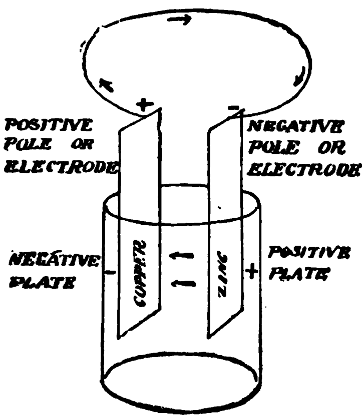


Fig. 73.—Nomenclature of a Voltaic Cell.

69. Detector Galvanometer.—

Exp. 10: From Exp. 9 it was shown that if a current passes over a needle it is deflected to the east or west, according to the direction of the current. The student should now prove that the needle is deflected oppositely if the wire be held underneath, but parallel to it, according to the direction of current in the wire. Note also that for the *same direction* of current underneath the needle as above it, the deflection is opposite to what it previously was. Now bend the wire around the needle, at rest, parallel to it, so that the current flows over the needle and under the needle in opposite directions. The deflection is now in the same direction, and *greater* than before. Make several convolutions and the deflection is still increased, Fig. 74. A few turns of wire wrapped around a pocket compass, parallel

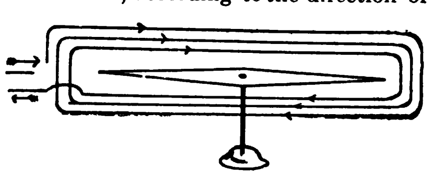


Fig. 74.—Simple Detector Galvanometer.

to the needle when it is pointing **N.** and **S.**, constitutes a simple form of *detector galvanometer*, and when inserted in a battery circuit will indicate by the deflection of the needle that a current is flowing. Various types of galvanometers are described in Lesson XVI.

70. Potential and Electromotive Force.—Suppose two vessels partially filled with water are connected by a pipe and placed on a table at the same level. The connecting pipe is full of water, yet there is *no current* of water flowing through the pipe because the pressure at each end is *the same.* When one vessel, A, Fig. 75, is raised above the other, B, then there is a *difference in pressure* between the two ends of the pipe, and a current of water *flows* from the *higher* to the *lower* level, due to this difference of pressure (or head) between the two points. It is not necessary to know the height of vessel A or B above the sea level, but the height or head (H) between the two vessels Similarly, if two points on a copper bar are elevated to the same temperature there is no transference of heat from one point to the other. If, however, one point is at a higher temperature than the other there is then a difference in temperature between the points and a transference of heat from the point of higher to the point of lower temperature.

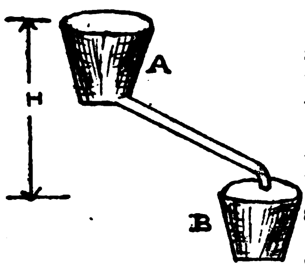


Fig. 75.—Water Analogy for Potential Difference.

The word *potential* as used in an electric sense is analogous to pressure in gases, head in liquids, and temperature in heat. In the Volta cell then we have two bodies raised to different electrical potentials (see ¶ 62), and to the difference of potential between them is due the current flowing through the wire connecting the plates. The greater this difference of potential the greater the current, or effect of the current produced.

Potential is the force which moves electricity through the circuit. The total force required to cause the current to flow through the entire circuit is called the *Electromotive Force,* whereas a *difference of potential* would exist between two points in a circuit, which would cause the current to flow just between these two points. Electromotive force (abbre-

viated E. M. F.) is the total difference of potential (abbreviated P. D.) that is maintained in any circuit.

Exp. 11: Insert two similar pieces of copper or zinc in the acidulated tumbler of water and test for a current by a detector galvanometer. The needle is not deflected. The similar plates being both electrified to the same degree there is no difference of potential between them, hence no current. This is analogous to the two vessels of water placed on a level.

71. Chemical Action in a Voltaic Cell.—A continuous potential difference is maintained between the zinc and copper plates when they are connected chiefly by the action of the exciting liquid upon the zinc. The chemist symbolizes sulphuric acid, H_2SO_4, meaning that it is composed of two parts hydrogen (H_2), one part sulphur (S), and four parts oxygen (O_4). The SO_4 part of the acid has a strong affinity for the zinc, and when the cell circuit is completed, attacks the zinc and forms zinc sulphate ($ZnSO_4$) which is dissolved in the water, and may be reclaimed by filtering after considerable zinc has wasted away. For every portion of the SO_4 part of the sulphuric acid which unites with the zinc, two parts of hydrogen gas are liberated, which escape from the solution as already noted in the experiments. The zinc thus replaces the hydrogen in the acid, setting it free. The chemical action may be expressed as follows:

$$Zn + H_2SO_4 = ZnSO_4 + H_2.$$

Zinc and sulphuric acid produce zinc sulphate and hydrogen.

Every time the circuit of a cell is completed, and as long as it is completed, this chemical action takes place, the zinc gradually wasting away, also the power of the acid to attack the zinc gradually becoming exhausted. Thus the electrical energy is maintained in the external circuit to perform useful work by the expenditure of so many pounds of zinc and acid inside the cell. The chemical energy contained in a lump of coal is converted into kinetic energy when burned under a steam boiler. Zinc might be similarly burned to produce steam, but its cost would be prohibitive, and for this reason batteries are not cheap generators of electricity for electric lighting and power purposes. In coal and zinc there is stored up chemical energy which may be expended by bringing together suitable substances and converted into heat and electrical energy, as is done when zinc is practically burned in a battery.

72. Why the Hydrogen Appears at the Copper Plate.—As already stated, when zinc is immersed in sulphuric acid, hydrogen is liberated and rises in bubbles to the surface of the solution. In the voltaic cell it was noticed that the hydrogen bubbles rose from the copper, yet no bubbles were seen to pass through the solution. Many chemists believe that the instant an element is liberated from a compound (as the H_2 from the H_2SO_4) it possesses unusual readiness to enter into combination with other molecules. At the instant the circuit is closed, Fig. 76, the SO_4 of molecule 1 unites with a molecule of zinc, setting free a molecule of hydrogen; this instantly unites with the SO_4 of molecule 2, forming a new molecule of H_2SO_4 and setting free the H_2 of molecule 2. This action continues until the last free molecule of H_2 appears at the copper plate and rises to the surface.

73. Polarization.

Exp. 12: Connect a Volta cell to a detector galvanometer wound with a few turns of wire and note the angle of deflection of the needle. Allow the current to flow for a while, and note that the deflection

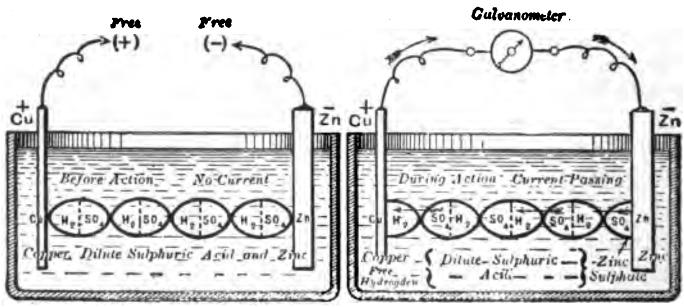


Fig. 76.—The Chemical Action in a Voltaic Cell when the Circuit is Closed.
The molecules of dilute sulphuric acid are represented by the ovals.

gradually falls and becomes much less than at first. Brush off the bubbles adhering to the hydrogen plate with a swab and the deflection is increased, thus indicating a stronger current; but it soon falls again when the copper plate becomes coated with the hydrogen gas.

The copper plate coated with hydrogen becomes practically a hydrogen plate. Now the effect of using a plate of hydrogen and zinc in a cell would be to set up a current from the hydrogen to the zinc inside the cell and from the zinc to the hydrogen outside of the cell. As this tendency acts against

the direction of the ordinary copper to zinc current it weakens the current from the cell. When the cell becomes weakened in this manner by a coating of hydrogen bubbles on the negative plate it is said to be polarized and the phenomenon called *polarization*. Polarization, then, is an evil, which, if properly overcome by arresting the bubbles in some manner, would permit the cell to give a strong current as long as any zinc remained to be acted upon. The attempt to prevent the polarization has given us the many varied types of cells now on the market.

The following test made on a Leclanche cell, ¶ 88, will illustrate the phenomenon of polarization. The cell was connected to a circuit of low resistance, and readings of a voltmeter, ¶ 235, were taken at one-minute intervals for five minutes, in which the E. M. F. dropped from 1.41 to .63 volts. The cell was then allowed to stand on open circuit for five minutes, and one-minute readings taken, to note its *recuperation*. At the end of the fifth minute the former E. M. F. was not regained, but only 1.18 volts. One-half hour after the test, a measurement then made showed the original E. M. F. of 1.41 volts.

Table II.—Polarization Test.

Discharge.		Recuperation.	
0 minutes,	1.41 volts.	0 minutes,	.63 volts
1 "	1.03 "	1 "	.87 "
2 "	.80 "	2 "	.97 "
3 "	.70 "	3 "	1.06 "
4 "	.65 "	4 "	1.14 "
5 "	.63 "	5 "	1.18 "

74. On What the Electromotive Force of a Cell Depends.—If two similar plates of zinc are immersed in an acid solution, Exp. 11, and connected, there is a tendency to opposite currents, which neutralize each other; since there is no difference of potential between them, no current flows. *The essential parts of any cell, then, are two dissimilar metals immersed in an acid solution, one of which is more readily acted upon by the acid than the other.* The greater the difference in intensity of chemical action the greater the difference of potential, and the greater the current strength which depends upon the difference of potential.

Other metals than copper and zinc may be used in cells, and as acids attack the different metals with varying intensities of chemical action, some combinations will produce better results than others. For example, a cell composed of zinc and lead plates, immersed in dilute sulphuric acid, will

not deflect a magnetic needle to so great an angle as a zinc copper cell of the same size, because a higher difference of potential is set up between zinc and copper than between zinc and lead.

The electromotive force of a cell is dependent also on the solution used to attack the zinc, so that the same battery plates immersed in different acids would indicate different potential differences, for the combination in each solution used. Using the same solution, however, this force is independent of the size of the plates, *a small battery having the same potential difference, or E. M. F., as a large one of the same kind*

In the following list of substances, known as the *electro-chemical series*, those most acted upon (electro-positive plates) by dilute sulphuric acid are placed at the left-hand of the list, while those least acted upon (negative plates) are at the right-hand end of the list.

The arrangement would be different for other acids used.

Table III.—The Electro-chemical Series.

Direction of current through external circuit.

←————

Positive plates.	Zinc.	Iron.	Tin.	Lead.	Copper.	Silver.	Platinum.	Carbon.	Negative plates.

————→

Direction of current through solution.

The difference of potential in a lead-silver cell would be less than a lead-carbon cell, while an iron-carbon cell would be greater, and a zinc-carbon cell still greater. For this reason zinc and carbon, being cheap commercial products, are extensively used in batteries. The arrows indicate the direction of current through the internal and external circuits. In a lead-carbon cell the carbon would be the positive and the lead the negative terminal; while in a lead-zinc cell the lead is the positive terminal and the zinc the negative terminal. Considering the plates in the list, any substance is *positive* to any substance which *follows* it, and *negative* to any *preceding* it.

Exp. 13: Using some similar strips of lead, copper, carbon, and zinc, make up different types of cells in dilute sulphuric acid. Connect each combination to the detector galvanometer and note the direction that the needle swings, the value of the deflection, and to which terminal each plate was connected. Note that when *lead* is connected to the *same terminal* of the galvanometer, and *carbon* used with it, the deflection is in the *opposite direction* to that when *zinc* is used with *lead,* which illustrates that in one instance the current leaves the lead terminal (+), and in the other instance flows to it (—).

Student's Experimental Cell.—A simple form of experimental cell with which numerous experiments can be made is illustrated in Fig. 76–A. A glass U tube is clamped to a vertical block on a base support by means of a rubber band. Suitable connections on the top of the block afford means for rapidly inserting rods, of the different metals in the electro-chemical series, in the electrolyte held in the U tube, and the chemical action is clearly visible. The device may be used as an electrolytic cell, also as a calorimeter when an iron wire spiral is inserted in the tube, and, again, as a convenient fuse block for determining the heating and fusing effects of the current on the different metals.

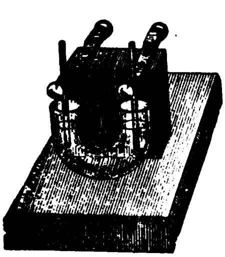


Fig. 76-A.—Student's Experimental Cell.

Exp. 14: Connect a galvanometer wound with *many turns* of *fine wire* to a Volta cell and note the value of the needle's deflection. Slowly withdraw the plates from the liquid and you note that the deflection of the needle remains the same until the circuit is broken at the surface of the liquid. This proves that the E. M. F. is independent of the area of the plates immersed. (See ¶ 74.) Move the plates further apart or closer together and the deflection is not changed, if the galvanometer is wound as above. The E. M. F. of a cell is independent of the distance between the plates.

75. Local Action.—When a pure piece of zinc (difficult to obtain) is used in a cell there is no action at the zinc except when the cell is in use. The ordinary commercial zinc contains many impurities, such as small particles of carbon, iron, tin, lead, etc., and when a rod of such zinc is placed in a cell these foreign particles form numerous local voltaic cells on the surface of the zinc inside the cell, with the result that the zinc is being continuously eaten away, whether the cell is in action or at rest. These small currents divert just so much strength from the regular battery current, thereby weakening it. Fig. 77 illustrates a magnified particle of iron on a zinc rod, and a local current

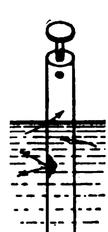


Fig. 77. Local Action.

would flow from the zinc to the iron through the solution and from the iron to the zinc across the junction. This is known as *local action.* In some cells local action is also caused by a difference in the density of the liquid at various parts of the cell. In this case the zinc near the top of the liquid is ordinarily wasted away, and may be entirely eaten off.

76. Amalgamation.—Local action may be prevented by thoroughly cleaning the zinc with sand paper, then immersing it in dilute sulphuric acid and while still wet applying mercury (quicksilver) by means of a rag swab. A bright amalgam is formed over the surface of the zinc and it is said to be *amalgamated.* The mercury dissolves the outer layer of zinc, forming a zinc-mercury amalgam. The foreign particles are either covered up from the action of the acid, or drop down to the bottom of the cell, or carried off by any remaining local action. The mercury does not prevent the zinc from being dissolved during the action of the cell, but continues to re-form an amalgam as the zinc wastes away. Zinc for battery plates is sometimes cast with a small percentage of mercury in its composition.

QUESTIONS.

1. Explain what you understand by the word electricity.
2. How does electricity manifest itself?
3. What is the action of dilute sulphuric acid on zinc?
4. What is a simple cell?
5. Explain the action in a simple voltaic cell. Give sketch.
6. Give your idea of a "current" of electricity.
7. What is an electrolyte?
8. Describe and illustrate Volta's pile.
9. What is meant by an open and closed circuit?
10. Distinguish between the internal and external circuit of a cell.
11. What are insulators?
12. What is meant by a good conductor?
13. State an experiment you would make to determine whether a body was an insulator or a conductor.
14. Give a reason for attributing direction to a current.
15. Which way does a current flow inside a Volta cell?
16. Sketch a simple Volta cell, name all the parts, and show the direction of the current in the internal and external circuit.
17. Distinguish between poles and plates.
18. Which is the negative electrode in a lead-copper cell in H_2SO_4?
19. Which is the positive plate in a lead-iron cell?
20. What is a detector galvanometer, and for what is it used? Give sketch.

LESSON IX.

BATTERIES.

Primary Batteries—Open Circuit Cells—Closed Circuit Cells—Remedies for Polarization—The E. M. F. of Cells—Smee Cell—Bichromate Cell—Fuller Bichromate Cell—Partz Acid Gravity Cell—Bunsen's and Grove's Cells—Daniell's Cell—Leclanche Cell—Gonda Leclanche Cell—Carbon Cylinder Cell—Edison-Lalande Cell—Chloride of Silver Cell—Dry Cells—Classification of Cells—Chemicals for Cells and Some Chemical Symbols—Questions.

77. Primary Batteries.—*Primary* batteries are so called to distinguish them from *secondary* batteries (storage batteries or accumulators, ¶ 107). Primary batteries are divided into two general classes, according to the manner in which they are to be used, known as *open circuit* cells and *closed circuit* cells.

78. Open Circuit Cells.—Open circuit cells are used for *intermittent work*, where the cell is in service for short periods of time, such as in electric bells, signaling work, and electric gas lighting. In cells of this class polarization does not have much opportunity to occur, since the circuit is closed for such a short period of time; hence, these cells are always ready to deliver a strong current when used intermittently. If kept in continuous service for any length of time the cell soon polarizes or "runs down," but will recuperate after remaining on open circuit for some little time.

79. Closed Circuit Cells.—In the *closed circuit* type of cell, *polarization is prevented* by chemical action, so that the current will be constant and steady till the energy of the chemicals is entirely expended. This type of cell is adapted for furnishing current continuously, as in the service of small lamps, motors, electroplating, etc.

80. Remedies for Polarization.—In the simplest form of cell, as zinc, copper, and dilute sulphuric acid, no attempt has been made to prevent the evil of polarization, ¶ 73; hence, it will quickly polarize when the circuit is closed for any length of time, and may be classified as an open circuit

cell. When polarization is remedied by chemical means the chemical added is one that has a strong affinity for hydrogen and will combine with it, thus preventing the covering of the negative plate with the hydrogen gas. The chemical used for this purpose is called the *depolarizer* and may be used either in a *solid* or *liquid* form, which gives rise to several forms of cells, such as cells with a single fluid. containing both the acid and the depolarizer; cells with a single exciting fluid and a solid depolarizer, and cells with two separate fluids. (See ¶ 94.)

In the *double fluid* form of cell the zinc is immersed in the liquid (frequently dilute sulphuric acid) to be decomposed by the action upon it, and the negative plate is surrounded by the liquid depolarizer, which will be decomposed by the hydrogen gas it arrests, thereby preventing polarization. The two liquids are sometimes separated by a porous partition of unglazed earthenware, keeping the liquids from mixing, except very slowly, but not preventing the passage of hydrogen or electricity.

Place sufficient mercury in a small battery jar to cover the bottom and fill the jar with a sal-ammoniac solution. Suspend a piece of zinc from the top of the jar and you have a zinc-mercury cell. Make connections with the mercury by a piece of rubber-covered wire. Connect the cell to a short coil galvanometer and note the falling deflection of the needle, due to polarization. When the cell becomes sufficiently polarized drop into the solution a piece of mercuric chloride ($HgCl_2$) the size of a pin head. The galvanometer needle instantly shows a much larger deflection. The hydrogen has been removed by the chlorine in the mercuric chloride. When the chlorine becomes exhausted polarization sets in again. The mercuric chloride is thus a chemical depolarizer.

81. The E. M. F. of Cells.—Considering the electromotive force of one particular type of cell as a standard of E. M. F., another type of cell will possess either a greater or less force in comparison with it. The unit of electromotive force is called the volt, and is about the pressure set up by a Volta cell, so that if a cell has an E. M. F. of 1.4 volts we mean that it possesses 1.4 times the force of a Volta cell. Cells are, therefore, rated by their E. M. F. In ¶136 will be found a table of E. M. F.'s of the different types of cells.

82. Smee Cell.—This cell is an example of the mechanical means used to overcome polarization. A plate of lead or silver is suspended between two zinc plates in dilute sul-

phuric acid. The silver or lead plate is covered with a fine, powdery deposit of platinum, which gives the surface a rough character, so that the bubbles of hydrogen will not readily adhere to it as they are formed, but rise to the surface of the solution. Another mechanical method to overcome polarization is to rotate the electro-negative plate, thus preventing bubbles of gas from adhering to it; but as this necessitates a constant force to keep the plate in motion, the cell would not be very economical. No *mechanical* method can wholly prevent the collection of hydrogen on the negative plate. This can only be accomplished by furnishing some chemical with which the hydrogen, as soon as it is liberated, will combine. The E. M. F. of a Smee cell is about 0.65 volt.

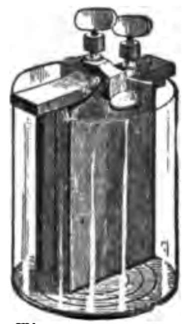


Fig. 78.—Smee Cell.

83. Bichromate Cell.—In this type of cell polarization is prevented by chemically arresting the hydrogen gas, so that it never reaches the negative plate. The same will be true of most of the cells now to be described. Bichromate of soda or bichromate of potassium is the depolarizer, to which is added water and sulphuric acid for attacking the zinc. The bichromates are rich in oxygen, for which hydrogen has a strong affinity. Carbon and zinc plates are used, and this type made up in several forms and termed chromic acid cells. In the Grenet (Gren-ā') form a zinc plate is suspended by a rod between two carbon plates, Fig. 79, so that it does not touch them, and when the cell is not in use the zinc is withdrawn from the solution by raising and fastening the rod by means of a set-screw, as the acid attacks the zinc when the cell is on open circuit. This cell has an E. M. F. of over 2 volts at first, and gives a strong current for a short time, but the liquid soon becomes exhausted, as will be noted by the change in the color of the solution from an orange to a dark red, and must be replenished. The zinc should be kept well amalgamated and out of the solution except when in use. It is a good type of cell for experimental work, and about two cells would perform nearly all of the experiments in this book. A simple substitute for this type of cell would be a number of electric light carbons fastened together to form the negative plate and several zinc rods for the positive

plate, which could be removed at will and then rinsed in water.

To make a solution for a bichromate cell take 3 ounces of finely powdered bichromate of potash and 1 pint of boiling water; stir with a glass rod, and after it is cool add slowly, stirring all the time, 3 ounces of sulphuric acid. The solution should not be used until cool. In mixing a battery solution always *pour the acid* gently *into the water*, while stirring, to dissipate the heat. *Never pour water into acid.* If bichromate of soda is used as above take 4 ounces bichromate of soda, $1\frac{1}{4}$ pints boiling water, and 3 ounces of sulphuric acid. These battery solutions are sometimes termed *electropoin* fluids.

Fig. 79.—Grenet Cell. Zinc and carbon in bichromate solution.

84. Fuller Bichromate Cell.—This double fluid cell has the advantage over the Grenet type, in that the zinc is always kept well amalgamated and does not require removal from the solution. A pyramidal block of zinc, to which a metallic rod covered with gutta-percha is attached, is placed in the bottom of a porous cup, Fig. 80, and an ounce of mercury is poured in. The cup is filled with a very dilute solution of sulphuric acid or water, and then placed in a glass or earthen jar containing the bichromate solution and the carbon plate. The acid diffuses through the porous cup rapidly enough to attack the zinc, which, being well amalgamated, prevents local action. The hydrogen travels from the zinc through the porous cup and combines with the oxygen in the potassium bichromate. The E. M. F. is about 2.14 volts, and the cell is used for open circuit or semi-closed circuit work. Another form of the Fuller type is shown in Fig. 81.

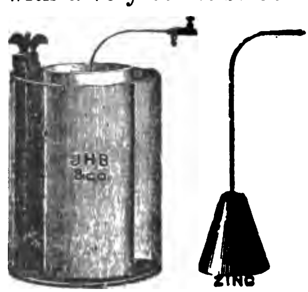


Fig. 80.—Fuller Cell. Zinc in dilute H_2SO_4 in porous cup, carbon in a bichromate solution.

85. Partz Acid Gravity Cell.—In the Partz acid gravity form of cell, Fig. 81-A, the electrolyte which surrounds the zinc is either magnesium sulphate or common salt.

Fig. 81.—Fuller Cell.

Zinc in porous cup with mercury and dilute H_2SO_4, carbon in a bichromate solution.

The depolarizer is a bichromate solution which surrounds the perforated carbon plate located in the bottom of the jar. A vertical carbon rod fits snugly into the tapered hole in the carbon plate, and extends through the cover forming the positive pole. The depolarizer, being heavier than the electrolyte, remains at the bottom of the jar, and the two liquids are thus kept separate. This depolarizer is placed on the market in the form of crystals, known as sulpho-chromic salt, made by the action of sulphuric acid upon chromic acid. When dissolved, its action is similar to that of the chromic acid solution. After the cell has been set up with everything else in place the crystals are introduced into the solution, near the bottom of the jar, through the vertical glass tube shown, and slowly dissolve and diffuse over the surface of the carbon plate. When the cell cur-

Fig. 81-A.—Partz Cell.

rent weakens a few tablespoonfuls of the salt introduced through the tube will restore the current to its normal value. The cell should remain undisturbed to prevent the solution from mixing. Its E. M. F. is from 1.9 to 2 volts, and the 6 in. x 8 in. size has an internal resistance of about .5 ohm. Since the depolarization is quite effective, the cell may be used on open or closed circuit work.

86. Bunsen and Grove Cells.—These cells are examples of the two fluid type, in which the solutions are separated by a porous partition. Bunsen's battery has a bar of carbon immersed in strong nitric acid contained in a porous cup. This cup is then placed in another vessel containing

Fig. 82.—Bunsen Cell.
Carbon in HNO_3 porous cup, zinc in dilute H_2SO_4.

Fig. 83.—Grove Cell.
Platinum in HNO_3 in porous cup, zinc in dilute H_2SO_4.

dilute sulphuric acid, and immersed in the same liquid is a hollow, cylindrical plate of zinc, which nearly surrounds the porous cup. The hydrogen, starting at the zinc, traverses, by composition and recomposition, the sulphuric acid, passes through the porous partition, and immediately enters into chemical action with the nitric acid, so that none of it reaches the carbon. There are produced by this action water, which in time dilutes the acid, and orange-colored poisonous fumes of nitric oxide, which rise from the battery. If the nitric acid first be saturated with nitrate of ammonia, the acid will last longer and the fumes be prevented. Strong sulphuric acid cannot be used in any battery; generally 12 parts by

weight, or 20 by volume, of water are added to one part of sulphuric acid.

Grove used a strip of *platinum instead* of *carbon* in his cell. A solution of bichromate of potassium (as in ¶ 83) is frequently substituted for the nitric acid in the porous cup, thereby avoiding disagreeable fumes. Bunsen's and Grove's batteries produce powerful and constant currents, and are well adapted for experiments, but they require frequent attention, and are expensive, so that they are little used for work of long duration. E. M. F., of these cells, 1.75 to 1.95 volts

87. Daniell Cell.—This battery is made in many forms and called by various names, such as Gravity battery, Bluestone Cell, Crowfoot battery, etc. An explanation of the theory

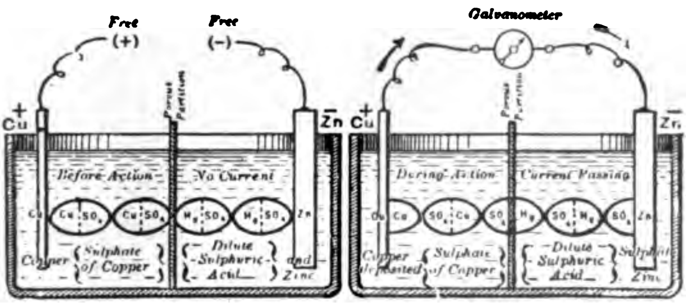
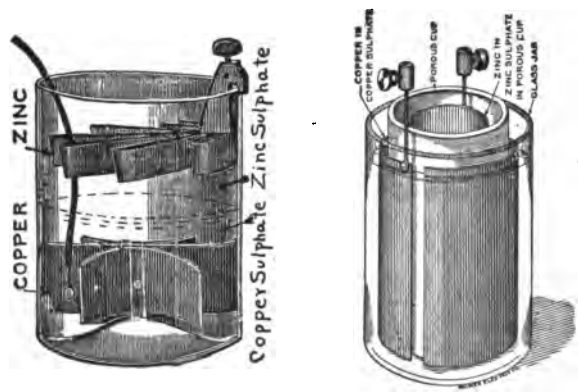


Fig. 84.—Chemical Action in the Daniell Cell when the Circuit is Closed.

of a simple form will answer for all forms of this class, and it is of importance, since the cell is much used in practice for giving constant currents of long duration. It is, therefore, a closed circuit battery. Zinc and copper elements are used. In Fig. 84 they are separated by a thin partition of unglazed pottery. On the zinc side of the partition is put dilute sulphuric acid (H_2SO_4), or simply water, if the cell is not required for immediate use; on the copper side is placed sulphate of copper ($CuSO_4$), dissolved in water, together with some sulphate of copper crystals (bluestone) to maintain the supply of copper sulphate solution. When the circuit is closed, as shown by Fig. 84, the zinc combines with the (SO_4) of the sulphuric acid forming sulphate of zinc ($ZnSO_4$), and thus sets free the two molecules of hydrogen (H_2).

This hydrogen gas passes through the porous partition, but instead of collecting on the sides of the copper plate, it meets with the sulphate of copper ($CuSO_4$), and having a greater natural affinity for the (SO_4) than the copper (Cu) possesses, it displaces the copper, and forms sulphuric acid, (H_2SO_4) setting free pure metallic copper, which is deposited upon the copper plate. This continuous extraction of metallic copper from the solution would soon weaken it, were it not for the fact that the copper crystals dissolve and thus automatically keep the solution saturated. To maintain a



Gravity Daniell Cell. Fig. 85. Student's Porous Cup Daniell Cell.

constant current for an indefinite time, therefore, it is only necessary to keep the supply of copper crystals and zinc maintained. The cell has an E. M. F. of about one volt and gives a small, but steady current. The "gravity type" of this cell, which is used in this country for telegraphy (closed circuit work), is illustrated in Fig. 85.

A student's small Daniell cell is also shown in Fig. 85. It is of the double fluid type. A rod of freshly amalgamated zinc is placed in the porous cup in a solution of zinc sulphate, with a specific gravity of 1.1. The porous cup is placed in a glass jar containing a solution of copper sulphate of the same specific gravity, and surrounded by a sheet of copper. It is advisable to short-circuit the cell for about ten minutes before using. Under the above conditions the E. M. F. is 1.05 volts. The cell should be set up with a new solution each time it is required and taken apart and cleaned after use. The cur-

rent on short circuit is small, about ½ ampere, but since polarization is eliminated it is a good cell to use for electrical measurements where a constant source of E. M. F. is required, as in Lesson XXI.

88. Leclanche Cell.—This very common form of cell is an example of the single solution type, with a solid depolarizer surrounding the negative element, which is generally carbon, the positive element being zinc, Fig. 86. The liquid used is a strong solution of ammonium chloride, commonly known as sal-ammoniac, and much resembles table salt. In the porous cup type of cell, a carbon slab is placed in the porous cup and surrounded by a mixture of small pieces of carbon and manganese dioxide, the top being covered by means of pitch, leaving one or two small holes for air and gas to pass through. The depolarizer will take care of a limited amount of the hydrogen produced when the cell is on closed circuit, but if the circuit be closed for any length of time polarization occurs. The cell is thus of the open circuit class, and will furnish a good current where it is required only intermittently. Zinc is dissolved only when the cell is being used. This type of cell, or its modification, is used for gas lighting and bell work. The cell requires very little attention. Water must be added as the solution evaporates, and the zinc rod replenished when necessary. The E. M. F. is about 1.48 volts and the internal resistance is about 4 ohms.

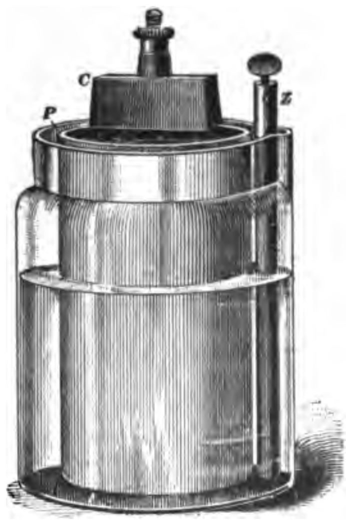


Fig. 86.—Leclanche Cell.
Carbon in porous cup with MnO_2, zinc in sal-ammoniac solution.

Directions for setting up the Leclanche Cell.—1. Place in the glass jar six ounces of ammonium chloride (sal-ammoniac), pour in water until the jar is one-third full and stir thoroughly.

2. Put in the porous cup, and add water if necessary until the level of the water is within 1½ inches of the top of the porous cup.

3. Put the zinc in place and set the cell away, without connecting up, for ten or twelve hours, to allow the liquid to thoroughly soak

into the porous cup, which will lower its level to about two-thirds the height of the jar, at which level it should be kept, by adding water as it evaporates. The cell is then ready for use.

89. Gonda Leclanche Cell.—This cell is a modification of the porous cup type, in which the manganese has been mixed with some gelatinous binder, and compressed into slabs, under hydraulic pressure. Two such slabs or prisms, one on each side of the carbon plate, are held in position by rubber bands, Fig. 87. A zinc rod and a sal-ammoniac solution are used. This cell was designed to dispense with the porous cup.

Fig. 87.—Gonda Leclanche Elements.

90. Carbon Cylinder Cell.—Carbon possesses a natural power to prevent a limited amount of polarization by absorbing the hydrogen gas coming from the zinc rod, so that we find it used in a variety of shapes for open circuit cells, which gives rise to as many different names, such as *Samson*, *Hercules*, *Law*, *National*, *Standard*, etc.

In all these types of cells, Fig. 88, sal-ammoniac and zinc are used, and by corrugating the carbon, fluting it, or making concentric cylinders, special merits are obtained in each case. Fig. 89 illustrates a carbon cylinder

Fig. 88.—Elements of a Carbon Cylinder Cell.

Zinc, carbon and sal-ammoniac solution.

cell of the Standard Carbon Co., in which the carbon is made in the form of a porous cup and then filled with oxide of manganese to prevent polarization. Still another form of the same make is shown in Fig. 90, in which the space between the two concentric carbon cylinders has been filled with oxide of

Fig. 89.—Elements of Carbon Cylinder Cell with Depolarizer.
Zinc, manganese dioxide in a porous cup and sal-ammoniac solution.

manganese and then sealed in. The zinc rod is prevented from touching the carbon by being first inserted through a porcelain insulator. About 4 to 6 ounces of sal-ammoniac are generally used for cells of ordinary size. The salt is placed in the jar, water poured in until it is about two-thirds full, and then stirred till all the salt is dissolved. When the carbon cylinder is inserted the solution should be within 1½ inches of the top of the jar. These cells should not be put in warm places, as over the heater in a cellar, on account of the rapid evaporation of the electrolyte. The E. M. F. is from 1.4 to 1.6 volts for the different forms of this type.

Fig. 90.
Section through carbon cylinder showing MnO_2 depolarizer.

91. Edison-Lalande Cell.—As in the Leclanche type, this cell is a single fluid battery with solid depolarizer, but is admirably adapted for use on *closed circuit work*, as for small motors, electrotyping, telegraphy, etc. Zinc is the positive, and black oxide of copper (CuO), the negative element. The exciting liquid is a solution of caustic potash. The oxide of copper is obtained by the process of roasting copper turnings; it is then

ground into a fine powder and compressed into solid blocks, from which plates of a suitable size are cut.

These plates are suspended from the cover of the battery jar, Fig. 91, by a light framework of copper, one end of the framework terminating as the positive pole of the battery. On each side of the copper oxide element is suspended a zinc plate, which is prevented from coming into contact with the copper oxide plate by means of vulcanite buttons. When the circuit is closed and the cell in action, the water is decomposed, the oxygen, forming with the zinc, oxide of zinc, which in turn combines with the potash to form a double salt of zinc and potash, which dissolves as rapidly as it is formed. The hydrogen liberated by the decomposition of the water reduces the copper oxide to metallic copper. The reduced copper is of great purity and can again be converted into copper oxide. It is important to see that the oxide plates are entirely submerged in the caustic potash solution. Heavy paraffin oil is poured on top of the solution, so as to form a layer about one-quarter inch deep on the surface, to keep out the air. When oil is not used creeping salts are formed and the life of the battery is reduced fully two-thirds. The E. M. F. is low, only 0.7 of a volt, but the internal resistance is also very low, so that quite a large current can be drawn from the cell. It is made in a number of different sizes, ¶ 140.

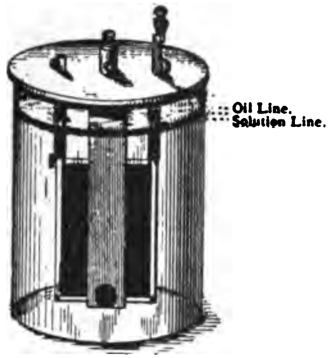


Fig. 91.—Edison-Lalande Cell. Zinc and copper oxide in caustic potash solution.

92. Chloride of Silver Cell.—This cell is another example of the single fluid type with a solid depolarizer, and is used extensively in portable testing sets where a large number of small cells are mounted in a case. The elements are small wires, or rods of zinc and silver, and on the silver is cast the solid depolarizer, silver chloride, which is reduced to metallic silver by the hydrogen gas. The chloride of silver may be melted in a porcelain crucible and cast around the wire in a carbon mold. A small cylinder of vegetable

parchment surrounds the silver wire and the chloride, to prevent internal short circuits. The zinc rod and silver wire are held in a paraffin stopper, the silver wire of one cell being wedged into the zinc rod of the next, and so on, when a number are connected in series. The elements are sealed in a small glass tube containing the electrolyte, which may be zinc sulphate, zinc chloride, or caustic potash. With zinc sulphate the E. M. F. is 1.1 volts.

Fig. 92.—Dry Cell.

93. Dry Cells.—These cells differ from those already described, in that the exciting fluid is combined with some special absorbent, such as sawdust, etc., or is made into a jelly. In the Gassner type of cell the zinc element is in the form of a cylinder, which holds the other element (carbon) and the exciting mixture. The carbon rod or plate occupies about one-half the space in the cell, and the space between the carbon and zinc cylinder is filled with the following mixture, the proportions being by weight: Oxide of zinc, 1 part; sal-ammoniac, 1 part; plaster, 3 parts; chloride of zinc, 1 part; water, 2 parts. Dry cells being portable, are very convenient for use where only an intermittent current is required. The E. M. F. is about 1.4 volts.

94. Classification of Cells.—

Batteries { Primary. / Secondary.

Primary batteries:

Classified by polarization into { Open circuit cells—(Grenet, Leclanche.) / Closed circuit cells—(Daniell, Lalande, Fuller.)

Classified by construction into { Single fluid cells—(Grenet, Leclanche, Lalande.) / Double fluid cells—(Bunsen, Grove, Daniell, Fuller.)

Single fluid cells with { Liquid depolarizer—(Grenet type.) / Solid depolarizer—(Leclanche, Lalande.)

Double fluid cells with liquid depolarizer—(Bunsen, Grove, Daniell.)

95. Chemicals for Cells and Some Chemical Symbols.—
Copper Sulphate (blue vitriol), $CuSO_4$
Zinc Sulphate (white vitriol), $ZnSO_4$
Ammonium Chloride (sal-ammoniac), NH_4Cl
Bichromate of Soda, $Na_2Cr_2O_7$
Bichromate of Potassium, $K_2Cr_2O_7$

Chromic Acid, CrO_3	Lead Peroxide, PbO_2
Caustic Potash, KOH	Sulphuric Acid, H_2SO_4
Caustic Soda, NaOH	Nitric Acid, HNO_3
Copper Oxide, CuO	Hydrochloric Acid, HCl
Manganese Dioxide, MnO	Silver Chloride, AgCl
Lead Oxide, PbO	Zinc Chloride, $ZnCl_2$

QUESTIONS.

1. Since the hydrogen gas is evolved from the zinc when it is placed in dilute acid, how do you account for the fact that in a Volta cell when connected to a circuit, the hydrogen gas is evolved at the copper plate, yet the copper is not attacked by the acid?
2. Upon what does the E. M. F. of a cell depend?
3. Would you expect a very large cell to have the same E. M. F. as a small one of the same kind made up in test tube? Why?
4. Give a list of some materials used in cells, in the order of their potential difference in dilute sulphuric acid.
5. A cell is composed of copper and iron in dilute sulphuric acid. Draw a sketch indicating the + and — plates and electrodes, and the direction of current, when the plates are connected.
6. Of what use is local action in a cell? How is it prevented?
7. What is the distinction between open and closed circuit cells?
8. Why are there so many different makes of cells on the market, and what is the general distinction between them?
9. Describe a two-fluid cell. Give an example.
10. What is a depolarizer? Give an example of a cell with a solid and liquid depolarizer, and state how the depolarizer acts in each.
11. Describe the Daniell cell and illustrate the chemical action.
12. Describe a bichromate cell of the Grenet type. Make a sketch.
13. How does the Fuller cell differ from the Grenet cell, since the chemicals and plates used are identical?
14. Describe the Leclanche porous cup type of cell. How is polarization prevented in this cell?
15. How does the Edison-Lalande cell differ from the Leclanche cell, since they both use solid depolarizers?
16. Which of the two cells mentioned in question 15 would you use for a spark-ignitor on a gas engine?
17. In what respect does a dry cell differ from a fluid cell?
18. Form a table of all the cells you know of, giving the + and — plates, electrolyte used, depolarizers, name and type (open or closed circuit) in the different columns of the table.
19. Describe fully the action of the Edison-Lalande cell.

LESSON X.

ELECTROLYSIS.

Effects of the Current—Heating Effect—Magnetic Effect—Chemical Effect—Electrolysis—Electrolysis of Copper Sulphate—Electrolysis of Zinc Sulphate—Electrolysis of Lead Acetate—Electroplating—Electrotyping—Polarity Indicator—Secondary Batteries, Storage Batteries or Accumulators—Direction of Current in an Accumulator on Charge and Discharge—Commercial Storage Batteries—Questions.

96. Effects of the Current.—A current of electricity is not a material substance, and, therefore, has no dimensions (length, breadth, or weight) by which it can be studied or measured. *An electric current is studied by the effects it produces, all of which are commercially utilized.* The effects manifested by a current of electricity are: *Heating Effect, Magnetic Effect, Chemical Effect,* and *Physiological Effect.* The first three of these effects are treated in this book. A current passed through the body produces muscular contractions, which are said to be due to the physiological effect. Electro-therapeutics deals with the study of this effect.

By a *direct* or *continuous current* is meant one which flows always in the same direction and has the same strength, as, for example, the current from a battery. In a *pulsating current* the direction is uniform, but the current strength varies. Most direct current dynamos furnish a pulsating current, but the pulsations are so rapid that the current becomes practically continuous. In an *alternating current* the direction is reversed at short intervals, and the current strength also varies periodically. Dynamos, called alternators, furnish such a current. The variations occur so rapidly that the current appears to be constant in the circuit.*

97. Heating Effect.—

Exp. 15: Connect the terminals of a bichromate cell to a piece of No. 32 iron wire about one inch long. The wire becomes so hot that

*In most of the following pages the references to current strength are true for direct currents, and exceptions must be made if other currents are considered.

it is luminous, illustrating both the *heating* and *lighting* effects of a current of electricity. The chemical energy inside of the cell is thus converted into electrical energy outside of the cell in the form of heat and light. If the current is strong enough the wire will be entirely melted.

Exp. 16: Substitute a piece of copper wire of the same size and length as the iron wire in Exp. 15. A smaller change of temperature will be noted.

Exp. 17: Close the circuit of the cell without any fine wire in the circuit. More heat is now generated inside of the cell than in the external conducting wires.

Every wire which conducts a current of electricity becomes heated to some extent as a result of the current, because the best conductors offer some opposition (resistance) to the flow of the current, and it is in overcoming this resistance that the heat is developed. If the wire is large in cross-sectional area and the current small, the heat developed will be so small in amount as not to be recognized by the touch, yet, nevertheless, some heat is evolved from the wire; upon the other hand, with a small wire and a large current it becomes quite hot. As the heat increases with the resistance of the conductor used, by employing a poor conductor we obtain both light and heat. This principle is used in the incandescent electric lamp, in which **a high resistance solid conductor called the filament is enclosed in a glass bulb from which the air has been exhausted, thereby preventing combustion of the filament. The current is passed through the filament and heats it to a state of incandescence.** Fig. 93 depicts **a carbon filament lamp, and of the electric energy expended in this type of lamp, only about 5 per cent. is represented by the light emitted, while the balance appears as heat, so that such a lamp, while convenient, is not an efficient source of illumination,** ¶383. The heating effect of the current is also utilized in the various electric cooking utensils on the market, in electric welding, electric smelting, and in reducing metals from their ores.

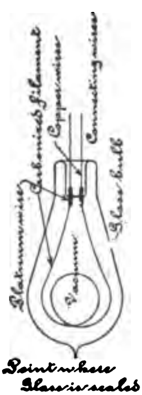


Fig. 93.—Electric Incandescent Lamp.

98. Magnetic Effect.—A wire carrying a current of electricity deflects a magnetic needle. When insulated and coiled around an iron core the current magnetises the core. **If the current flowing through a wire be sufficiently strong, the wire**

will attract iron filings, proving the existence of the magnetic field around the wire. This subject is treated under Electro-magnetism, Lesson XV.

99. Chemical Effect.—We have noted in a simple Volta cell, ¶ 71, how electrolytic decomposition takes place inside the cell when a current is flowing. The current is also capable of decomposing certain chemical compounds (liquids) outside of the cell, when it is passed through them, breaking up the compounds into their constituent parts. Liquids may be divided into three classes: (1) *Those which do not conduct electricity at all*, such as many of the oils, particularly petroleum; (2) *liquids which conduct without decomposition*, as mercury and molten metals, which conduct just as solids; (3) *liquids which are decomposed when they conduct a current*, as the dilute acids, solutions of metallic salts, and some fused compounds.

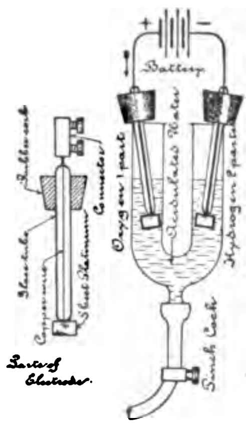


Fig. 94.—Glass U Tube with Electrodes Forming an Electrolytic Cell.

Exp. 18: Electrolysis of Water.—Fill the U tube, Fig. 94, with water, and add a few drops of sulphuric acid to make the liquid a better conductor. Connect the terminals of two bichromate cells joined in series, ¶ 141, to the two platinum terminals shown in the U tube, so that the circuit from the cells will be completed through the acidulated water. Have the corks quite loose in the U tube for the gases to escape. When the circuit is completed bubbles of gas immediately rise from both platinum plates, more, however from the platinum plate connected with the negative pole of the battery. The *gases may be collected separately by the forms of apparatus shown in Figs. 99 and 100*, or collected together in one tube in the form of voltameter shown in Fig. 97.

During this electro-chemical action the current decomposes the water, liberating hydrogen gas at the negative battery pole, and oxygen gas at the positive battery pole. Twice as much hydrogen as oxygen gas is liberated. Water is composed of these two gases, hydrogen and oxygen, in the proportion of two parts of hydrogen to one of oxygen (or H_2O) and the current breaks up the water into its constituent parts, Fig. 97. If brass or copper plates are used, the positive plate will be attacked by the action, and no oxygen will be evolved.

Exp. 19: Reverse the direction of the current through the solution by changing the battery terminals, and note that the hydrogen and oxygen gases are now liberated on the opposite electrodes from Exp. 18, which is another reason for supposing that the current has direction; the opposite deflections of the magnetic needle being a former proof.

100. Electrolysis.—A large number of chemical compounds in a state of fusion, or dissolved in certain solvents can, like the acidulated water, be separated into their constituent parts by the passage of an electric current through them. Any substance that is capable of being decomposed by an electric current is called an *electrolyte* (as in a Volta cell) and the process is termed *electrolysis* (meaning loosening by electricity). Plates of carbon, lead, platinum or other metals are used to conduct the current to and from the solution, according to the substance to be electrolyzed.

These plates are called electrodes, and the plate by which the current *enters* the electrolyte is called the positive electrode or *anode* and the plate by which it *leaves* the solution is called the negative electrode or *cathode.* The constituent parts of the electrolyte which are liberated at the surface of the electrodes are called *ions;* the ion liberated at the positive electrode being called the *anion*, and that which appears at the negative electrode the *cathion.* Any vessel or apparatus used for performing or measuring electrolysis is called a *voltameter.* In the electrolysis of water hydrogen is the cathion and oxygen the anion.

101. Electrolysis of Copper Sulphate.—

Exp. 20: Fill the U tube, Fig. 94, with a solution of copper sulphate, made by dissolving some copper sulphate crystals (bluestone) in water, and subject the solution to electrolysis, as in the case of the water, using platinum electrodes. Metallic copper is deposited upon the negative electrode, that is the plate becomes copper-plated. Oxygen gas is liberated at the positive platinum electrode and sulphuric acid is formed.

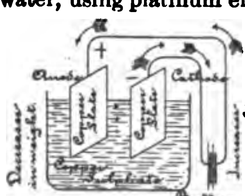


Fig. 95.—Copper Voltameter.

The chemical symbol for copper sulphate is $CuSO_4$ and by electrolysis it is separated into Cu (metallic copper) and SO_4 (sulphion). The hydrogen gas liberated at the negative plate displaces the Cu of the $CuSO_4$ forming H_2SO_4 (sulphuric acid), and deposes the Cu on the negative plate, while oxygen gas is liberated at the + platinum plate,

as before. If the action is allowed to continue for some time, all the metallic copper is taken from the solution and deposed. This will be noted by the solution changing from a deep to a pale blue, as the change gradually takes place from copper sulphate to sulphuric acid. The action is represented as follows:

$$\underset{\text{Sulphate of copper}}{CuSO_4} \quad \underset{\text{becomes}}{=} \quad \underset{\text{copper}}{Cu} \quad \underset{\text{and}}{+} \quad \underset{\text{sulphion}}{SO_4}$$

$$\underset{\text{Sulphion}}{SO_4} \quad \underset{\text{and}}{+} \quad \underset{\text{water}}{H_2O} \quad \underset{\text{produce}}{=} \quad \underset{\text{sulphuric acid}}{H_2SO_4} \quad \underset{\text{and}}{+} \quad \underset{\text{oxygen}}{O}$$

Exp. 21: Reverse the direction of current in Exp. 20 and note that now the copper-coated platinum plate becomes the positive electrode, with a platinum plate for the negative electrode. The latter has metallic copper deposed upon it, while the former metallic copper on the positive plate is returned again to the solution.

Exp. 22: Substitute two copper electrodes for the platinum electrodes and repeat Exp. 20. Metallic copper is again deposited upon the negative electrode (increasing its weight) but from the positive electrode no gas is evolved, yet this plate wastes away, or is dissolved in the solution, thereby losing in weight.

When a copper positive plate is used, the $CuSO_4$ is separated into Cu on the negative plate, and SO_4 which attacks the positive plate, and forms a new molecule of $CuSO_4$ (copper sulphate). Thus as a molecule of copper sulphate is decomposed, a new molecule is formed, keeping the solution constant. Just as much metallic copper is thrown down into solution from the positive plate, as is taken from the solution and deposed on the negative plate. The art of electroplating is based on the above experiments.

102. Electrolysis of Zinc Sulphate.—

Exp. 23: Dissolve some crystals of zinc sulphate, $ZnSO_4$ (white vitriol) in water. Refill the U tube, Fig. 94, with this solution and subject it to electrolysis. Use platinum electrodes and metallic zinc is deposited upon the negative electrode and oxygen gas is evolved from the positive electrode. Reverse the direction of current. The previously deposited zinc is deposed again into solution while the other electrode now receives a deposit of zinc. Oxygen gas is not evolved from the positive electrode till all of the zinc has been thrown down into solution.

Exp. 24: Repeat Exp. 23, using two zinc strips as electrodes, and note that the positive strip wastes away, and the negative zinc strip gains in weight. The action of the *Edison electrolytic meter* for measuring current is dependent upon this principle, being then a zinc voltameter.

103. Electrolysis of Lead Acetate.—

Exp. 25. Prepare a solution of lead acetate, and pass it through filter paper to clear the solution. Fill the U tube, Fig. 94, and subject it to electrolysis, using platinum electrodes. Metallic lead is deposited at the negative plate, and oxygen gas appears at the positive plate. In addition to coating the platinum plate the lead will be deposited in a beautiful tree-like form extending out into the solution from the negative plate. The solution becomes weaker as the extraction of metallic lead continues. When the current is reversed, the former positive plate receives the deposit in the "tree form," but oxygen gas is not now liberated from the positive plate, until the lead previously deposited is dissolved in the solution. This experiment is very suitable for illustration in a lantern projection cell, as well as for laboratory work.

104. Electroplating.—The art of depositing a coating of metal upon any object is termed electroplating, and is based upon the principles of electrolysis already explained. The metal held in solution is always deposited on the object to be plated, which must be connected to the negative pole of the source of electricity, while a plate of the metal from which the coating is derived, as nickel, copper, gold, or silver is used as the positive plate. In plating with gold or silver the bath (electrolyte) is always alkaline, and generally a cyanide of the metal to be deposited is used for the solution. In plating an iron spoon with silver, for example, the iron is cleaned, to remove all dirt and grease, and then first receives a deposit of copper in a copper bath, as silver will not deposit upon iron. Articles of iron, steel, zinc, tin, and lead cannot be silvered or gilded unless first coated with a thin covering of copper ✓ After a thin coating of copper, the spoon is transferred to a silver bath, properly connected up and a coating of the desired thickness deposited, after which it is cleaned and brightened on a buffing wheel.

Other substances beside metals can be electroplated by first preparing the surface with a coating of powdered graphite, or plumbago, upon which metal can be deposited. A very low voltage is used in electroplating, since the character of the deposit depends upon the density or strength of current used, ¶ 123. If electrolytic action takes place too rapidly, the deposit is soft, coarse-grained, and liable to prove unsatisfactory, while a small current gives a good, hard, close-grained deposit. The potential varies with the electrolytes used, generally from 1 to 3 volts being applied to the bath.

105. Electrotyping.—Suppose an electrotype is desired

from a column of standing type. An impression in wax, or plaster of Paris, is carefully made of the type, and the wax mould dusted over with powdered graphite to make the surface a conductor. The mould is connected as the negative plate in a copper plating bath and receives a thin coating of metallic copper. After removal from the bath the copper deposit is removed from the mould and backed, or filled in with type metal to about the depth of one-eighth inch. When cool, the back is planed smooth, fastened to a block of wood, and can then be used in the press. The copper mould is generally so thin that it is necessary to back it up with the type metal, owing to the pressure to which the electrotype is to be subjected. In this manner the electrotypes for the pages of many books are made from the standing type, and may be used for taking thousands of impressions.

106. Polarity Indicator.—The positive and negative poles of a direct current electric light, or power circuit, can be determined by dipping the terminals, at some little distance apart, into a tumbler of water. As twice as much hydrogen gas is evolved at the negative wire as oxygen at the positive wire, the polarity of the circuit is readily determined. Care must be taken not to bring the wires into contact, or some damage would occur, due to too much current flowing through such a low resistance circuit. A solution of iodide of potassium, with a little starch added, is sometimes sealed in a glass tube and terminals provided, by which a current can be passed through, and the polarity of the circuit determined. This is called a polarity indicator. Iodine is liberated at the positive terminal and turns the starch blue around this terminal.

107. Secondary Batteries, Storage Batteries or Accumulators.—

Exp. 26.—Place two copper strips in a solution of zinc sulphate contained in a small battery jar. Connect the terminals of the copper strips to a galvanometer, and note that the needle is *not* deflected, because the combination does not conform to the definition of a voltaic cell, ¶ 63. Disconnect, and substitute for the galvanometer, two bichromate cells connected in series (connect carbon to zinc). By electrolysis, hydrogen gas would be evolved at the negative plate, but having a greater affinity for the SO_4 part of the zinc sulphate ($ZnSO_4$), than the zinc, it displaces it, forming sulphuric acid (H_2SO_4) and metallic zinc is deposed on the negative copper plate. After the action continues a little while, disconnect the battery and again connect the electrolytic cell to the galvanometer and note that the needle is now deflected.

A secondary battery, storage battery or accumulator, is a voltaic cell, the positive and negative plates of which are formed or deposited by electrolysis, produced by a separate source of electricity. *No electricity was stored* in Exp. 26, but a chemical action took place, which changed the plates into two dissimilar metals and the salt (zinc sulphate) into an acid, capable of attacking one of them, thus conforming to the definition of a primary cell. The current performing the electrolysis is termed the *charging current*, and the secondary cell is said to be *charged*, meaning that it will again generate current when connected to a circuit. This is called *discharging* the cell. The chemical action on discharge of our simple type of accumulator will be obviously the same as in the Volta cell, since the plates (copper-zinc) and the acid formed (sulphuric) are identical with the Volta cell. On discharge, the zinc is decomposed by the acid, and when it is all dissolved in the solution the cell is entirely discharged and must be re-charged again by electrolysis.

108. Direction of Current in an Accumulator on Charge and Discharge.—Upon charging the accumulator, Exp. 26, the direction of current inside the cell was from copper to zinc; upon discharge, the current inside the cell travels in the opposite direction (zinc to copper, as in a Volta cell), so that the positive terminal of an accumulator is connected to the *positive* terminal of the charging lines, and this same terminal will again be positive on discharge.

Exp. 27: Fill the U tube with acidulated water and connect the voltameter, Fig. 99, to two bichromate cells. After passing the current for a short time, causing an evolution of gas, disconnect the batteries and connect the voltameter to a galvanometer. A deflection of the needle indicates that a current is now passing through the voltameter in an opposite direction to the former battery current.

109. Commercial Storage Batteries.—

Exp. 28: Place two lead strips in the U tube, Fig. 94, fill with acidulated water and connect the plates to a detector galvanometer. No deflection is noted. Now connect the plates to two bichromate cells (in series), and after passing a current for a short time examine the plates, and you will find that the positive plate has become brownish in color, while the negative plate is the same as before. Connect the plates to the galvanometer, and note that the needle indicates the discharging current.

Lead plates in dilute sulphuric acid were first used by Planté, from whom this type of cell takes its name. The

action in charging such a cell is as follows: Electrolysis of water liberates oxygen on one plate (the positive) which combines with the lead to form lead peroxide (PbO_2), while hydrogen accumulates on the other plate (the negative). On discharging the cell the oxygen of the peroxide plate combines with the hydrogen of the liquid, liberating oxygen, which, in turn, combines with the hydrogen of an adjacent molecule, until finally the hydrogen on the other plate is reached. Commercial lead storage batteries are modifications of the above type; when charged, the positive plate *active material* becomes lead peroxide and the negative spongy lead. As discharge takes place the positive material reduces to lead oxide (PbO), and the negative oxidizes also to PbO; continuing the discharge results in the formation of lead sulphate ($PbSO_4$) on the positive plate. This insoluble sulphate increases the resistance of the cell and reduces its capacity. For this reason storage cells should never be over-discharged or allowed to remain in that condition for any length of time before being charged, for the reason that great damage may result, the battery plates warping or "buckling," due to the insoluble sulphate collecting in the active material, causing it to expand and contract, and as lead has very little elasticity, mechanical strains are produced in the plate, causing them to bend. The E. M. F. of a lead storage cell when fully charged is about 2.2 volts. The cell should never be discharged below 1.8 volts. The discharging current depends upon the area of the plates used, while the length of discharge depends upon the weight of the plates. In order to have as large plate area as possible, a number of grids are fastened to one terminal, forming the negative plate, and one less than this number form the positive or active plate. The solution used is dilute sulphuric acid, having a specific gravity of 1.2 to 1.24 when cell is fully charged; on discharge the specific gravity should never fall below from 1.185 to 1.195.

Fig. 96.—Chloride Accumulator.
Positive element, one plate; negative element, two plates.

Fig. 96. shows an accumulator of the chloride type. In this type the "Box Negative" is used, the *active material* is enclosed in intersecting ribs of the grid, and held in place by perforated sheet lead on two sides, the two sides being riveted together. The active material, formed from lead chloride, is metallic lead in a spongy or porous form. The *positive* plate consists of a lead-antimony grid having circular holes ⅝ inch in diameter, the holes being filled with a spiral button made of corrugated pure lead ribbon. The *active material* peroxide of lead is formed on the surface of these buttons by electro-chemical process. During the forming process the plugs expand, thus improving the contact between them and the grid.

The above cell is particularly adapted for heavy duty, as in central station work. Where high capacity in proportion to weight is required, as in vehicle work, the Electric Storage Battery Co., Philadelphia, brought out the "Exide Cell," the positive plate consisting of a lattice work grid, in the interstices of which the active material, lead peroxide in paste form, is forced under hydraulic pressure.

QUESTIONS.

1. Name all the effects of an electric current and give a commercial application of each.
2. Explain the principle of an electric incandescent lamp.
3. How would you classify liquids according to their conducting power, and the chemical effect of the current upon them?
4. (*a*) What is an electrolyte? (*b*) What is electrolysis?
5. Define the terms anion, cathode, anode, cathion.
6. Give the action in the copper voltameter, also a sketch.
7. Give two reasons for inferring that current has direction.
8. What is the action in a copper voltameter when a platinum plate is substituted for a copper plate? Give sketch.
9. What is a polarity indicator, and how is it used?
10. What is an accumulator?
11. How does a storage battery differ from a primary battery?
12. What does a storage battery store?
13. Explain the action in a simple type of storage battery.
14. What is meant by the terms charging and discharging?
15. How would you connect a storage battery to a circuit to be charged? Show by a sketch the polarity of the cell and the polarity of the charging line.
16. Describe fully a commercial type of storage battery. State the actions on charge and discharge. Give sketch.

LESSON XI.

MEASUREMENT OF CURRENT STRENGTH.

Strength of Current—Variation of Current and Current's Effects—How the Effects Vary with the Current Strength—Variation of Effects with the Same Current Strength Through Dissimilar Apparatus—Measurement of Current Strength—Definition of the Unit of Current Strength—Definition of a Unit Quantity of Current—The Ampere-Hour—Weight Voltameters—Voltameter Calculations—Construction of the Gas Voltameter—Directions for Using the Gas Voltameter—Measuring Current Strength by a Gas Voltameter—Current Strength Used in Electroplating and in Commercial Apparatus—Questions and Problems.

110. Strength of Current.—Either the magnetic, heating, or chemical effect of an electric current may be employed to determine whether a current is flowing through a wire. If the magnetic effect of a current flowing through a wire is greater than that of another current, the *intensity* of the current, or the *strength* of the current, must be greater, since the magnitude of any of the current's effects varies with the current assumed to be flowing. We express the rate of flow of water through a pipe as so many *gallons per second*, which expression includes a definite quantity of water and a unit of time; that is, at a rate of flow of one gallon per second, we mean that one gallon passes any point in the pipe once every second. By the *strength of an electric current* we mean the rate of transfer of electricity past any point in the circuit in a unit of time (the second). It is obvious that the magnitude of the effects of the current may be used to measure the strength of the current.

111. Variation of Current and Current's Effects.—

Exp. 29: Pass a current under a force of one volt through a coarse wire galvanometer and note the deflection. Repeat the experiment with twice the applied pressure, two volts, and the deflection of the magnetic needle is *less than twice* as much as before, although the *force* is *doubled* and the *current strength*, varying as the force, must also *have been doubled.*

Exp. 30: With an applied pressure of 4 volts note the amount of gas generated from dilute sulphuric acid in 2 minutes by the appara-

tus in Fig. 99. Repeat the experiment with 8 volts and note that in the same time twice the volume of gas is generated.

Exp. 31: Using copper sulphate and two copper plates, carefully weighed before the test, apply a force of 2 volts for 10 minutes and then re-weigh the plates. The negative plate has gained in weight exactly what the positive plate lost. Repeat the experiment with 4 volts for the same length of time and the weight is increased to double what it was before.

Exp. 32: Coil a number of turns of No. 30 iron wire around the bulb of a thermometer, and place it in a small test tube containing a measured quantity of water. Place the test tube in a larger vessel containing sawdust to prevent heat radiation. Apply a force of 4 volts for 10 minutes and by aid of the thermometer note the rise in the temperature of the water. Repeat the experiment with 8 volts for the same period of time, with the same quantity of water, and at the previous starting temperature. Neglecting the heat lost by radiation, the increase of temperature is nearly four times as great as in the first test, although the current was only doubled. If the current had been tripled, the temperature rise would have been 9 degrees, and with *the current* quadrupled the rise would have been 16 degrees, and so on.

112. How the Effects Vary with the Current Strength. The above experiments may be made simultaneously when the circuit is arranged, as in Fig. 97, in which nearly all the effects of the current are represented. The circuit is made up as follows: starting from the positive battery terminal the current would flow (1) through a few turns of coarse wire in the galvanometer coil; (2) a large number of turns of coarse wire on the spools of the electromagnet; (3) a dilute solution of sulphuric acid in the mixed gas voltameter, the current to pass between platinum electrodes; (4) a solution of copper sulphate, the current to pass between copper electrodes; (5) a number of turns of No. 30 iron wire wound around the bulb of a thermometer and immersed in a vessel of water placed in sawdust; (6) through the carbon filament of an incandescent lamp; (7) through a switch to the negative pole of the battery, and (8) from the negative pole of the battery through it to the positive pole

When the switch is closed, the current produces the following effects simultaneously: The magnetic needle is deflected; it requires a certain number of pounds pull to detach the keeper from the electromagnet; hydrogen and oxygen gas rise in the graduated test tube, displacing the acidulated water therein; metallic copper is deposed from the copper positive plate and deposited upon the copper negative plate, so that it thereby gains in weight; heat is evolved in the

vessel containing the iron coil of wire; very dim light is given by the incandescent lamp; zinc is being decomposed in the batteries furnishing the electrical energy to produce all these effects outside of the battery.

All the effects are produced the instant the switch is closed, but only four can be noted instantly—the needle's deflection, the attractive force of the magnet, the evolution of gas, and the brilliancy of the lamp. The weight of copper deposited, gas liberated, and the number of degrees rise in temperature, due to a current flowing for only an instant is so small as to be practically unmeasurable. By allowing the current to flow for a certain period of time a measurable quantity is obtained, which divided by the time in seconds gives the magnitude of the effect per second, or the current strength. Keep the switch closed for about five minutes ($5 \times 60 = 300$ seconds), then by dividing the volume of gas generated in 300 seconds by 300 we obtain the gas generated per second, and similarly with the gain in temperature and the gain in weight of the negative copper plate.

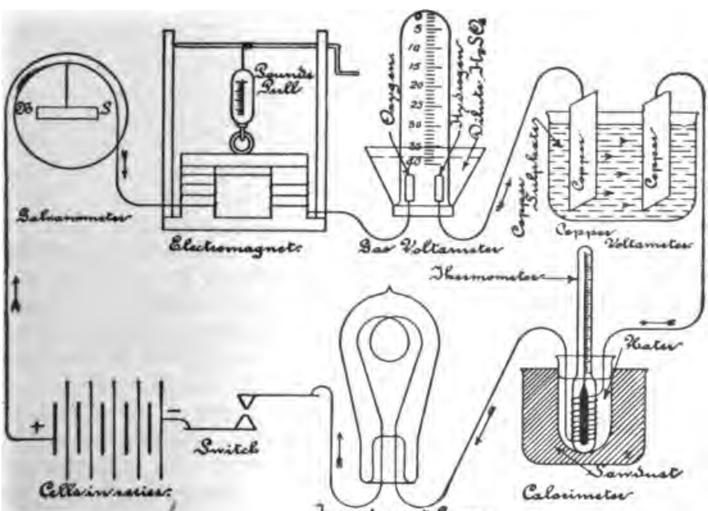


Fig. 97.—The Effects of the Current and their Variation with a Variation in Current Strength.

This is a simple series circuit and the current is the same in all parts of it.

We thus get a series of results of the different effects all corresponding to the same strength of an electric current, flowing for a unit of time. The intensity of current that deflected the needle in one part of the circuit, or magnetised the iron core of the electromagnet, is exactly the same as that which decomposed the acidulated water or the copper sulphate, or heated the iron wire. This is a simple *series* circuit, although made up of a number of different conductors, and the *current is the same in all parts of a series circuit;* that is, the rate of flow past any point selected is the same. The order of the arrangement of the apparatus is also immaterial. By increasing the E. M. F. of our battery so that twice the pressure is applied to this same circuit, we double the current strength or rate of flow. The switch is closed for the same time as before, and the results noted for comparison. A third test may also be made, using three times the force. The record of three such tests, with apparatus as arranged in Fig. 97, is as follows :

Tests of Current's Effects.

	Test 1.	Test 2.	Test 3.
Galvanometer, deflections	25	37	42
Electromagnet, pounds pull	54	65	70
Gas voltameter, volume of gas generated per second	.17	.34	.51
Copper voltameter, gain in weight per second	.0003	.0006	.0009
Calorimeter, degrees rise per second	.1	.4	.9
Incandescent lamp, candle-power	5	8	12

From the above tests the following facts will be noted : The deflection of the galvanometer needle is not directly proportional to the current, doubling the current, not doubling the deflection. The number of pounds pull, or attractive force, is not directly proportional to the current strength. The volume of gas generated is exactly proportional to the current, and if the current had been quadrupled the gas generated per second would have been four times as great, and so on. The deposit of copper is directly proportional to the current, doubling the current, also doubling the gain in weight. The rise in temperature was not doubled, but increased four-fold; with three times the current strength the rise is nine-fold, the temperature rise thus increases directly as the square of the current strength; for example, 1 unit of current produces 1 degree rise; 2 units, 4 degrees

rise; 3 units, 9 degrees rise, etc.; the lamp's luminosity is not directly proportional to the current.

113. Variation of Effects with the Same Current Strength Through Dissimilar Apparatus.—If the series circuit, Fig. 97, had contained two pieces of each apparatus of widely varying dimensions of plates, convolutions in the coils, size of wire, etc., what would have been the result? The current strength would have been the *same* in *each* part of the circuit as before. The fine wire galvanometer would produce a larger deflection than one of a few turns of the same diameter. The electromagnet, with the greater number of turns, would have the greater attracting power. A gas voltameter with small plates, widely separated, would evolve the *same volume* of gas as a voltameter with much larger plates placed close together, since the gas evolved is proportional to the rate of flow of electricity, which is the same through both instruments, and hence independent of the size of the electrodes or their distance apart. Similarly, in two copper voltameters in the *same* series circuit, the weight of copper deposited is independent of the size of the plates or their distance apart, and would be the same for each voltameter, however constructed. More heat would be generated by the coil of many turns of fine wire. The current flowing through a circuit is the same in all parts of that circuit; thus, if at two different points in a circuit a gas voltameter be inserted, the gas evolved at the one point will be exactly equal to that evolved at the other point.

114. Measurement of Current Strength.—To compare different strengths of current some arbitrary standard must be adopted. If we defined our unit of current strength as such a rate that flowing every second would deflect our magnetic needle, ¶ 112, 25 degrees, we would also have to specify the length of needle, diameter of coil, number of turns, place where the needle was set up, etc., which would make it an impractical standard. Also in the case of the electromagnet, all the dimensions and quality of the iron, the keeper and the wire, etc., would have to be stipulated. If we would express the unit of current strength as such a rate of flow that would attract a keeper with 54 pounds, then, again 2 units of current do not attract the keeper 108 pounds, as might be expected, but only 65 pounds. (See test, ¶ 112.) The current strength is directly proportional, however, to the

amount of gas generated per second or the amount of metal deposited per second, so that of all the effects the chemical one is the best adapted for furnishing a standard unit of current strength, since such a standard will be independent of the apparatus used to produce the effect. The heating and magnetic effects are employed in various practical instruments for measurements, but they are standardized by the chemical effect.

115. Definition of the Unit of Current Strength.—*The strength of current is directly proportional to the amount of chemical decomposition it can produce in a given time, and as a steady current passed through a solution of nitrate of silver in water, in a silver voltameter, deposits silver at the rate of 0.001118 grams per second, this value is taken as a unit of current strength and called one ampere.*

One ampere will deposit in one second:

.0003293 grams of copper in a copper voltameter;

.0003387 grams of zinc in a zinc voltameter.

One ampere will also decompose .00009334 grams of dilute sulphuric acid per second. One ampere will also evolve .1733 cubic centimeters of mixed gas per second in a gas voltameter (when the temperature is 0° Centigrade and the atmospheric pressure 76 centimeters of mercury).

116. Definition of a Unit Quantity of Electricity.—Distinction must be made between the total quantity of electricity that passes through a circuit in a given time, and the rate of flow of electricity during that time. For example, at the rate of flow of one gallon per second, 3600 gallons of water would be delivered to a tank in an hour, the total quantity being readily distinguished from the rate of flow. We might consider the *gallon per second* as a unit of quantity and name it, but this has not been done in hydraulics, although it is done in the case of electricity. The total quantity of water equals the rate multiplied by the time in seconds; thus, at a rate of flow of 8 gallons per second, in 60 seconds, the total quantity delivered would be 480 gallons, which same quantity could be delivered to a tank in one second if the rate were 480 gallons per second, or in one-half second if the rate were 960 gallons per second, or in 480 seconds if the rate were only one gallon per second. Similarly the *unit quantity of*

*Values given by Ayrton.

One ounce = 28.34 grams.

electricity is the amount of electricity that flows per second past any point in a circuit when the current strength is one ampere, and this unit quantity has been called the coulomb. If a current strength of one ampere flows for 60 seconds, then the total quantity is 60 ampere-seconds, or 60 coulombs of electricity.

FIRST: TO FIND THE TOTAL QUANTITY OF ELECTRICITY PASSING THROUGH A CIRCUIT IN A GIVEN TIME:

Multiply the current strength (expressed in amperes) by the time (expressed in seconds).

Let I = current strength in amperes;
Q = the total quantity of electricity in coulombs;
t = time the current flows (in seconds);

Then:

Quantity = current strength $\times$ time,
or coulombs = amperes $\times$ seconds,
or substituting the above symbols,

$$Q = I \times t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

Prob. 1: An incandescent lamp requires a current of one-half an ampere to maintain its proper brilliancy. If the lamp is lighted two hours what quantity of electricity will be consumed?

2 hours $= 60 \times 60 \times 2 = 7200$ seconds.
By Formula (1) $Q = I \times t = \frac{1}{2} \times 7200 = 3600$ coulombs.
$I = \frac{1}{2}$ ampere, $t = 7200$ seconds.

SECOND: TO FIND THE AVERAGE CURRENT STRENGTH (IN AMPERES) WHEN THE TIME THE CURRENT FLOWS, AND THE QUANTITY OF ELECTRICITY ARE KNOWN:

Divide the quantity (in coulombs) by the time (in seconds).

Current strength = Quantity $\div$ time,
or Amperes = Coulombs $\div$ Seconds,

$$\text{or Amperes} = \frac{\text{Coulombs}}{\text{Seconds}},$$

$$\text{or by substitution } I = \frac{Q}{t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Prob. 2: What is the average rate of current strength in a lamp circuit if the electrical consumption was 54000 coulombs and the current used for 5 hours?

5 hours $= 60 \times 60 \times 5 = 18000$ seconds.

$$\text{By Formula (2)} \quad I = \frac{Q}{t} = \frac{54000}{18000} = 3 \text{ amperes.}$$

$Q = 54000$ coulombs, $t = 18000$ seconds.

THIRD: TO FIND THE TIME (IN SECONDS) REQUIRED FOR A GIVEN QUANTITY OF ELECTRICITY (IN COULOMBS) TO PASS A POINT IN A CIRCUIT:

Divide the quantity of electricity (in coulombs) by the rate of flow (in amperes).

$$\text{Time} = \frac{\text{Quantity}}{\text{Current Strength}},$$

$$\text{or Seconds} = \frac{\text{Coulombs}}{\text{Amperes}},$$

$$\text{or by substitution } t = \frac{Q}{I} \quad \ldots\ldots\ldots\ldots \quad (3).$$

Prob. 3: How long a time will be required to pass 18000 coulombs through an electroplating bath if the average rate of current strength is 6 amperes?

By Formula (3) $t = \frac{Q}{I} = \frac{18000}{6} = 3000$ seconds, or $\frac{3000}{60} = 50$ minutes.

$Q = 18000$ coulombs, $I = 6$ amperes.

117. The Ampere-Hour.—The *coulomb* is a very *small unit* of quantity. A *larger unit*, the *ampere-hour*, is often used. One *ampere-hour* would be the quantity of electricity that would pass any point in a circuit in one hour, when the strength of current is one ampere. One ampere-hour obviously equals 2 amperes for one-half hour; 4 amperes for one-quarter hour, or one-quarter ampere for 4 hours and so on. One ampere-hour also equals 3600 coulombs.

The capacity of batteries is rated in ampere-hours. For example a 100 ampere-hour cell would mean one in which sufficient chemicals were present to maintain one ampere for 100 hours; 2 amperes, for 50 hours, etc. An ampere-hour recording meter is placed in a lamp circuit so that it will record the total quantity of electricity that has been utilized, or the total ampere-hours.

TO FIND THE AMPERE-HOURS CONSUMED BY ANY ELECTRICAL APPARATUS:

Multiply the average strength of current (in amperes) by the time (expressed in hours) that the current has been maintained.

$$\text{Ampere-hours (quantity)} = \text{Amperes} \times \text{hours};$$

$$\text{Amperes} = \frac{\text{Ampere-hours}}{\text{hours.}};$$

$$\text{Hours} = \frac{\text{Ampere-hours}}{\text{Amperes.}}.$$

Prob. 3-A: A current of 6.5 amperes was maintained by a cell for 4 hours. What quantity of electricity has been used?

Quantity = amperes × hours = 6.5 × 4 = 26 ampere-hours.
Suppose the cell has a capacity of 78 ampere-hours, how long could the above current be maintained?

$$\text{Hours} = \frac{\text{Quantity}}{\text{Amperes}} = \frac{78}{6.5} = 12 \text{ hours.}$$

118. Weight Voltameters.—Current strength may be determined by a weight voltameter, one in which the weight of metal deposited or weight of water decomposed, serves to determine the rate of flow; or a gas voltameter in which the volume of mixed gas to be evolved is used to determine the current strength. A weight voltameter is illustrated in Fig. 98. The two outside plates form the anode, and are joined together and to one binding post, while the cathode is placed between them and connected to the other binding post. The cathode thus receives a deposit on both sides. An adjustable arm serves to lower the plates into the electrolyte. A gas voltameter is described in ¶ 120.

Fig. 98.—Construction of a Weight Voltameter.
One cathode between two anodes.

119. Voltameter Calculations.—FIRST: TO CALCULATE THE STRENGTH OF AN UNKNOWN CURRENT (IN AMPERES) WHICH HAS PASSED THROUGH A WEIGHT VOLTAMETER:

Find the weight of metal deposited per second by dividing the total gain in weight by the time (in seconds) the current flows through the instrument; divide this quotient by the weight deposited by one ampere in one second, and the result is the strength of current expressed in amperes.

Let I = current strength in amperes;
W = total gain in weight;
t = time in seconds current flows;
K = weight deposited by one ampere in one second.

Substituting for the above statement then:

$$\text{Amperes} = \frac{\text{weight gained}}{\text{gain per ampere-sec.} \times \text{time.}},$$

$$\text{or } I = \frac{W}{K \times t} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4).$$

If W is expressed in grams:

K for a copper voltameter is .0003293 gram;
K for a zinc voltameter is .0003387 gram;
K for a silver voltameter is .001118 gram;
K for a sulphuric acid *weight* voltameter is .00009334 gram;
K for a sulphuric acid *gas* voltameter is .1733 cubic centimeter.

Prob. 4: The negative plate of a copper voltameter has increased in weight by 1.818 grams in thirty minutes. What was the average rate of current strength?

By Formula (4) $I = \frac{W}{K \times t} = \frac{1.818}{.0003293 \times 1800} = 3.067$ amperes.

K for copper is .0003293, $t = 30$ minutes $= 30 \times 60 = 1800$ sec.

SECOND: TO FIND THE WEIGHT OF ANY METAL THAT WILL BE DEPOSITED IN A VOLTAMETER BY A GIVEN CURRENT IN A GIVEN TIME:

Multiply the current strength by the time (in seconds) and this product by the weight deposited by one ampere in one second (K), the result is the weight expressed in grams (one pound = 453.59 grams).

$$\text{Weight (gained)} = \text{Current} \times \text{time} \times K,$$

$$\text{or } W = I \times t \times K \quad . \; . \; . \; . \; . \quad (5).$$

Prob. 5: In an electroplating bath how many grams of zinc will be deposited by a current of 5 amperes in 45 minutes?

By Formula (5) $W = I \times t \times K = 5 \times 2700 \times .0003387 = 4.5724$ grams.

K for zinc = .0003387.

$t = 45$ minutes $= 45 \times 60 = 2700$ seconds.

THIRD: TO FIND THE TIME REQUIRED TO ELECTROLYTICALLY DEPOSIT ANY GIVEN WEIGHT OF METAL WITH A GIVEN CURRENT STRENGTH:

Divide the weight by the current strength, and by the weight deposited by one ampere in one second (K), the result is the time expressed in seconds.

$$\text{Time} = \frac{\text{Weight (gained)}}{\text{Current} \times \text{K}},$$

$$\text{or t (seconds)} = \frac{W}{I \times K} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (6).$$

Prob. 6: How long a time will be required to deposit 5.9328 grams of silver on a copper-plated teaspoon with a current of 2 amperes?

By Formula (6) $t = \frac{W}{I \times K} = \frac{5.9328}{2 \times .001118} = 2653$ seconds, or $\frac{2653}{60}$ = 44 minutes 13 seconds.

K for silver = .001118 gram.

120. Construction of the Gas Voltameter.—The gas voltameter is convenient for individual laboratory use with a large body of students, as it obviates the necessity of a pair of scales for each student. A demonstration type of instrument is shown in Fig. 100. A student's voltameter is illustrated in Fig. 99, and is composed as follows:

1 brass stand (16 inches high)
1 glass U tube
2 platinum electrodes sealed in a glass tube and connected by a copper wire, to which connectors are attached
2 rubber corks for electrodes
1 glass burette, graduated from 0 to 30 cubic centimeters and reading in tenths of a cubic centimeter
2 adjustable clamps
8 inches rubber tubing
2 brass connectors
1 pinch cock, for use when it is used as an electrolytic cell for copper, etc.

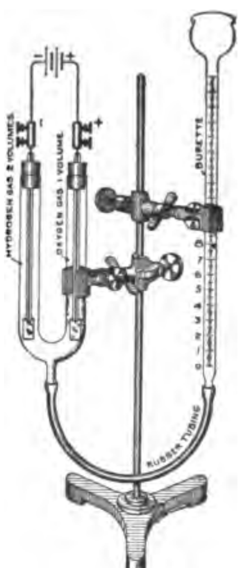


Fig. 99.—Student's Sulphuric Acid Gas Voltameter.

121. Directions for Using the Gas Voltameter.—

(1) Attach both clamps to the stand. (2) Attach one end of the rubber tube to the glass U tube and *carefully* clamp it by the lower clamp on to the stand. (3) Attach the other end of the rubber tube to the burette and *carefully* clamp it by the upper clamp. (4) Adjust the position of both clamps so that the zero position of the burette is about one-half inch below the level of the top of the U tube. (5) Pour the acidulated water into the mouth of the burette till the water in the U tube is about one-half inch from the top, the height of liquid in the burette should be on a level with or *above* the zero mark. (6) With the electrodes

inserted through the corks, place each one in position, *carefully*, by giving a slight twist to the right as the cork enters. (7) The water level in the U tube and burette should now be the same, or further adjustment must be made to attain this result. The level in the burette does not necessarily have to correspond with the zero graduation, but must not be below it. (8) Unclamp the burette and hold it nearly horizontal. The liquid will not run out if the corks are tight, so that this is the *air leakage test*. (9) Attach the connectors and wires from the source of E. M. F. (which should be 2 or more volts) having a final switch in the circuit.

In electrolyzing any substance a back or contrary E. M. F. is set up in opposition to the decomposing current, due to the chemical affinity of the substances dis-united, which tend to re-unite. Sufficient force must therefore be applied to overcome this force of chemical affinity. For example, in the case of water this opposing force is about 1.5 volts, so that it requires a greater force than 1.5 volts to electrolyze water, hence our two cells are joined in series.

Exp. 33: Close the switch connecting the above voltameter in circuit. Bubbles of gas rise in the U tube from both electrodes, displace the water and force it up the burette. Twice the volume of gas (hydrogen) is collected over the negative electrode that is collected over the positive electrode (oxygen). Run the test till the volume of hydrogen gas occupies nearly the whole limb of the U tube when the switch should be opened.

Exp. 34: With the gases collected in Exp. 33, lower the burette as far as possible (to decrease the hydrostatic head). Remove the cork for an instant from the hydrogen limb and *quickly* apply a lighted match. The hydrogen burns with a pale bluish flame. *Replace the cork quickly* so that the solution is not forced out of the U tube. Now remove the cork from the oxygen, extinguish the flame of the match and *quickly* apply the glowing spark to the oxygen; the match immediately bursts into a flame again. *Replace the cork quickly.* Oxygen gas does not burn, but supports combustion. If both gases are collected in a single tube, as in the form of the voltameter used in Fig. 97, when a lighted match is presented to the mouth of this tube the hydrogen, instead of burning, explodes with a violent report, due to the presence of the oxygen.

122. Measuring Current Strength by a Gas Voltameter.—FIRST: TO FIND THE CURRENT STRENGTH WHEN A VOLUME OF GAS IS EVOLVED IN A GIVEN TIME:

Divide the volume of gas evolved by the time (in seconds) and this quotient by the volume of gas evolved by one ampere in one second (K). The result is the current in amperes (subject to corrections when greater accuracy is required).*

*Neglecting temperature, barometric pressure and hydrostatic head.

$$\text{Current} = \frac{\text{volume of gas generated}}{\text{time (seconds)} \times K},$$

$$\text{or } I = \frac{V}{t \times K} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7).$$

K for the mixed gases or the two gases evolved separately = .1733 c. c. (¶ 115).

Second: The volume of gas (in cubic centimeters) which will be evolved by a given current in a given time is

$$\text{volume evolved (c. c.)} = \text{current} \times \text{time (seconds)} \times K,$$

$$\text{or } V = I \times t \times K \quad . \quad . \quad . \quad . \quad . \quad (8).$$

Third: Also the time required to evolve a certain quantity of gas with a given current is

$$\text{time (seconds)} = \frac{\text{volume}}{\text{Current} \times K},$$

$$\text{or } t = \frac{V}{I \times K} \quad . \quad . \quad . \quad . \quad . \quad (9).$$

Exp. 35: Set up the gas voltameter again according to the directions in ¶ 121. To correct error caused by the decrease in volume of the gases, due to the weight of the liquid in the burette at the end of the test, lower the burette before the test so that the height of liquid in it is about on a level with the bottom of the U tube. Secure a watch (preferably with a second hand). Note the level of the liquid on the burette scale before starting the test. Close the switch, noting the exact time. Allow the gas to be evolved till either the hydrogen limb of U tube is nearly full, or the liquid in the burette *approaches* the end of the scale. *Do not run above scale limit.* Note the time of opening the switch, also the *height* of the liquid in the burette.

Prob. 7: The following data is recorded in Exp. 35. Find the strength of current.

Level in burette before test 2.6 c. c.
Level in burette after test 28.8 c. c.
Volume of gas evolved = 28.8 — 2.6 = 26.2 c. c.
Time of closing switch 8.40 — 15.
Time of opening switch 8.45 — 15.
Length of run = 5 minutes = 5 × 60 = 300 seconds.

Total gas generated per second $= \frac{26.2}{300} = .0873$ c. c.

One ampere in one second (one coulomb) generates .1733 cubic centimeters of gas per second, therefore $\frac{0.0873}{.1733} = .5$ ampere,

or by Formula (7) $I = \frac{V}{K \times t} = \frac{26.2}{.1733 \times 300} = .5$ ampere.

When more accurate calculations are desired the following formula is used to find the current strength:

$$I = \frac{V \times h \times 273}{.1733 \times 76\,(273 + C^\circ) \times t} \quad \ldots\ldots\ldots\ldots \quad (10).$$

V = volume of gas in c. c.
h = height of barometer in centimeters.
C° = temperature of room, Centigrade, where test is made.
t = time (in seconds) gas is evolved.

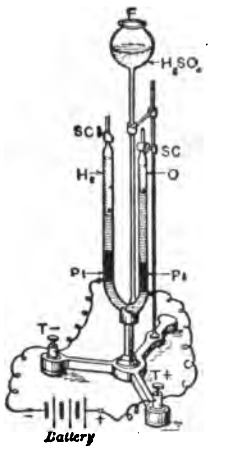


Fig. 100.—Gas Voltameter. Hoffman's Lecture Room Form.

Prob. 8: In an experiment the volume of gas generated in a gas voltameter was found to be 20 cubic centimeters in 50 seconds, its temperature (taken as the temperature of the room) was 20 degrees, Centigrade scale, the pressure of the atmosphere was equal to 75 centimeters of mercury. What was the current strength?

By Formula (10)

$$I = \frac{20 \times 75 \times 273}{.1733 \times 76\,(273 + 20) \times 50}$$
$$= 2.12 \text{ amperes.}$$

To find the volume of gas generated by a known current:

$$V = \frac{.1733 \times I \times 76\,(273 + C^\circ) \times t}{h \times 273} \quad \ldots \quad (11)$$

Prob. 9: What volume of gas would be produced in a gas voltameter in 30 seconds by a steady current of 18 amperes, supposing the temperature of the gas so produced is 20 degrees C. and the barometer stands at 77.5 centimeters?

By Formula (11) $$V = \frac{.1733 \times 18 \times 76\,(273 + 20) \times 30}{77.5 \times 273} = 98.49 \text{ c. c.}$$

123. Current Strength Used in Electroplating.—If the metallic deposition is performed too rapidly the deposit becomes open and of a powdery appearance. A low current density produces a hard, close grained surface. The usual densities used in practice are:

Copper acid bath, 5 to 10 amperes per square foot of area to be plated.
Copper cyanide bath, 3 to 5 amperes per square foot of area to be plated.
Nickel, double sulphate, 6 to 8 amperes per square foot of area to be plated.
Gold, chloride in cyanide, 1 to 2 amperes per square foot of area to be plated.
Silver, double cyanide, 2 to 5 amperes per square foot of area to be plated.

Prob. 10: A piece of sheet-iron, six inches square, is to be plated on both sides in a copper acid bath. What current strength is required?

From ¶ 123: Current density for copper cyanide bath is 5 to 10 amperes per square foot—

Say 8 amperes, 144 square inches = 1 square foot.

Area of plate (both sides) = 6 × 6 = 36 square inches × 2 = 72 square inches.

$\frac{72}{144} = .5$ square foot at 8 amperes per square foot = 4 amperes.

Table IV.—Value of Current Strengths Used in Practice.

The strength of current required to operate a 110 volt, 16 candle-power carbon incandescent lamp is about	0.5 ampere
For an enclosed 110 volt arc lamp	5 amperes
For an open-air arc lamp	8 to 10 amperes
For a trolley car equipped with two 25 horse power motors when fully loaded	75 amperes
For a 110 volt fan motor	$\frac{1}{2}$ to 2 amperes
For the average electric bell	$\frac{1}{10}$ ampere
For the average telegraphic circuit	.025 ampere
For 110 volt Weston voltmeter, full scale deflection	.0006 ampere
For electrical welding	20 to 50,000 amperes

QUESTIONS.

1. What do you understand by current strength?
2. State some experiments you would make to ascertain how the effect of a current varies with its strength.
3. Which effects of the current are directly proportional to it?
4. Which effects do not vary directly with the current strength?
5. An electromagnet attracts its keeper with a force of 18 pounds. If twice the E. M. F. be applied to the magnet coils, what will be the comparative result?
6. A coil of iron wire carrying a current is thrown into a tumbler of water for 10 minutes and the temperature is changed 6 degrees. The current is now exactly doubled for the same length of time. What is the change in temperature?
7. Which is the most suitable effect of the current by which it can be measured? Give reason for your answer.
8. What would be the objection to considering the standard unit of current strength, as of such a strength that would deflect a galvanometer needle 30 degrees?
9. A current strength is said to be 5 amperes. What do you understand by this expression?
10. What is the unit of current strength? Give example.
11. Explain the difference between the terms "current strength" and "quantity of electricity."
12. What is the unit of electrical quantity?
13. Five coulombs are used every second by a lamp. What is the current strength?

14. Why is it that you cannot electrolyze water with one Daniell cell?

15. Platinum and copper plates are dipped into a solution of zinc sulphate and a current passed from the platinum to the copper plate. How are the plates affected?

16. Give an example of chemical composition and deposition in the same circuit.

17. Copper and platinum plates are dipped into copper sulphate. What is the action when the current is passed from the copper to the platinum plate?

PROBLEMS.

1. How many ampere-hours will be recorded by a meter through which 160 amperes has passed for three-quarters of an hour? *Ans.* 120 ampere-hours.

2. A 100 ampere-hour Edison-Lalande cell is discharged through an electromagnet at a 2½ ampere rate. How long will the cell maintain this current through the magnet? *Ans.* 40 hours.

3. A meter records 500 ampere-hours. It was in circuit 5 days for 10 hours each day. What was the average rate of current used? *Ans.* 10 amperes.

4. How many coulombs have passed through an arc lamp in three-quarters of an hour if the current was 10 amperes? *Ans.* 27,000 coulombs.

5. What current strength is required to deposit 5 grams of copper upon an iron spoon in 35 minutes? *Ans.* 7.219 amperes.

6. A meter records 54,000 coulombs in 3 hours. What was the average strength of current? *Ans.* 5 amperes.

7. How many grams of copper will be deposited on an iron plate used for a ship's hull in 10 hours if the average strength of current is 25 amperes? *Ans.* 296.37 grams.

8. The two terminals of an electric light circuit are dipped into a tumbler containing 5 grams of acidulated water. How long would a current of 3 amperes flow before the water was entirely decomposed? *Ans.* 4 hours 57 min. 35 sec.

9. Using a current density of 5 amperes per square foot, how long a time is required to copper plate both sides of a square iron plate measuring 4 feet on a side, supposing sufficient thickness is attained when the coating weighs 4 grams per square foot? *Ans.* 40 min. 29 sec.

10. An inverted test tube, capacity 40 c. c., is filled with acidulated water, and the terminals, of several cells in series, are introduced underneath the tube. In 5 minutes half of the tube was filled by gas. What was the strength of current in the circuit? *Ans.* 0.384 ampere.

11. The negative zinc plate of an Edison electrolytic meter increased in weight during a certain time, 3.455 grams. This amount represents one one-thousandth part of the current used by the consumer. With how many ampere-hours should he be charged? *Ans.* 2833 ampere-hours.

12. What bill would you render for the current consumed in Prob. 11 if the station's rate was 1.5 cents per ampere-hour. *Ans.* $42.50.

LESSON XII.

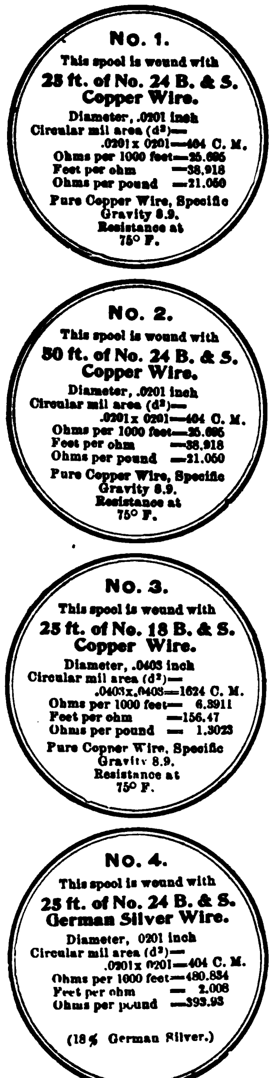
RESISTANCE.

Resistance—Table V. Conductors and Insulators—The Unit of Resistance—Laws of Resistance—Table VI. Resistance of a Mil-Foot of the Metals—Calculation of Resistance—Wire Measure—The Circular Mil—The Square Mil—The Wire Gauge—Specific Resistance, Relative Resistance and Conductivity of Metals—Internal Resistance of a Battery—Questions and Problems.

124. Resistance.—All bodies offer some opposition to the passage of an electric current through them. Pipes offer opposition to the flow of water through them, due to the friction between the running water and the sides of the pipes.

Electrical *resistance is the opposition offerea by any substance to the flow of an electric current through it.* No conducting body possesses perfect conductivity, but every conductor offers some resistance to the passage of a current. All bodies conduct differently, some offering more opposition to the flow of current than others. If the opposition is small, the conductivity is good, and the body is classed as a *conductor.* When the opposition (resistance) is high, the *conductivity* is poor, and the substance is classed as a poor conductor, which ranks it as a good *insulator.* The property of an insulator is to obstruct the flow of current. With a good conductor for conducting current, and a good insulator for confining it to the conductor, we have the practical conditions for handling electricity. The metals and alloys are good conductors. *Resistance* is the reciprocal of *conductivity.* The greater the conductivity of a body the less its resistance; the one decreases in the same ratio as the other increases. *Conductivity* (the property of conducting) is sometimes called *conductance.* *Resistance* is sometimes called *resistivity.*

Exp. 36: Connect spool 1 of the resistance spool set, Fig. 101, to a student's Daniell cell with the detector galvanometer, Fig. 153, in circuit, and note the deflection of the needle.



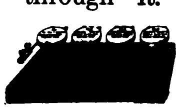


Fig. 101.—Resistance Spool Set.

Exp. 37: Connect spool 2 in place of 1, and note the deflection, which is smaller than before. Why?

Exp. 38: Connect spool 3 in place of 2, and note the deflection. It is greater than either 1 or 2. Why is this so, since it is of the same *length* and *material* as 1?

Exp. 39: Substitute spool 4 for 3, and note the deflection. This is smaller than in any of the other cases. Spool 4 is of exactly the same length and cross-sectional area as spool 1. Why is the deflection so much smaller?

Exp. 40: Connect several bichromate cells in series with spool 4, and pass a current through it for a short time. The spool becomes warm. Now connect it again in the same circuit as in Exp. 39, and note that the deflection is smaller than before. Why is this so, since it is exactly the same *length*, *area*, and *material* as in Exp. 39?

125. Conductors and Insulators.—In the following table the substances are arranged in the order of their *conductance*, the best conductors being at the top, and the best insulators at the bottom of the list. Any substance in the table is approximately a *better conductor* than any substance which *follows* it; thus, lead is a better conductor than mercury, but not so good as zinc. A slight variation in the quality of a substance would change its position in the list with reference to some other substance; for example, some marble is useless for switchboards on account of metallic veins running through it. The same is true of slate, so that the position of these substances on the list is approximate.

Table V.—Conductors and Insulators.

Good Conductors (metals and alloys).	Silver Copper Aluminum Zinc Brass (according to composition) Platinum Iron Nickel Tin Lead German silver (copper 2 parts, zinc 1, nickel 1) Platinoid (German silver 49 parts, tungsten 1 part) Antimony Mercury Bismuth.	
Fair Conductors.	Charcoal and coke Carbon Plumbago Acid solutions Sea water Saline solutions Metallic ores Living vegetable substances Moist earth.	
Partial Conductors.	Water The body Flame Linen Cotton Mahogany Pine Rosewood Lignum vitæ Teak Marble.	Mahogany, Pine, Rosewood, Lignum vitæ, Teak: Dry Woods.
Non-Conductors or Insulators.	Slate Oils Porcelain Dry leather Dry paper Wool Silk Sealing wax Sulphur Resin Gutta percha Shellac Ebonite	

(Continued on page 108.)

Non-Conductors or Insulators.	**Mica** **Jet** **Amber** **Paraffin wax** **Glass (varies with quality)** **Dry air.**

126. The Unit of Resistance.—The unit of resistance is called the *Ohm*, and is the resistance that would be offered to the flow of an unvarying electric current by a column of mercury 106.3 centimeters long, weighing 14.4521 grams in mass of a uniform cross-sectional area, at a temperature of 0° Centigrade (or 32° Fahrenheit). This is the *Legal Ohm*. In practice the value of the ohm, corresponding to the above standard, is as follows, *approximately:*

1 ohm = 1000 feet of copper wire $\frac{1}{10}$ inch diameter (No. 10 B. & S.).

1 ohm = 250 feet of copper wire $\frac{1}{20}$ inch diameter (No. 16 B. & S.).

1 ohm = 2 pounds of copper wire $\frac{1}{20}$ inch diameter (No. 16 B. & S.) or (125 feet per pound).

1000 feet of copper wire nearly $\frac{15}{32}$ inch diameter (0000 B. & S.) = .04967 ohm.

1000 feet of copper wire $\frac{3}{1000}$ inch diameter (40 B. & S.) = 1063 ohms.

In calculating or measuring very low resistances one-millionth of the value of an ohm is sometimes used and called the *microhm.*

To express a resistance in microhms multiply by 1,000,000 or

$$\text{Microhms} = \text{ohms} \times 1{,}000{,}000 \quad \ldots\ldots \quad (12).$$

$$\text{Ohms} = \frac{\text{microhms}}{1{,}000{,}000} \quad \ldots\ldots \quad (13).$$

In measuring very high resistances one million ohms are used as the unit and called a *megohm* (often abbreviated meg.).

$$\text{Megohms} = \frac{\text{ohms}}{1{,}000{,}000} \quad \ldots\ldots \quad (14).$$

$$\text{Ohms} = \text{megohms} \times 1{,}000{,}000 \quad \ldots\ldots \quad (15).$$

Prob. 11: What is the equivalent resistance in megohms of 47,500,000 ohms?

By Formula (14) $\frac{47,500,000}{1,000,000} = 47.5$ megohms.

Prob. 12: Give the equivalent resistance in microhms of .00385 ohm.

By Formula (12) $.00385 \times 1,000,000 = 3850$ microhms.

Prob. 13: What is the equivalent resistance in ohms of 225 microhms?

By Formula (13) $\frac{225}{1,000,000} = .000225$ ohm.

127. Laws of Resistance.—From the experiments made with the resistance spool set, ¶ 124, the following laws are deduced:

I. *It is the mass or weight* (cross-sectional area) *of a material which conducts and not its surface.* This can be proved by using a wire tube in comparison with a solid wire of the same diameter in the experiments in ¶ 124. Law I, Fig. 102.

II. *The resistance of a conductor is directly proportional to its length.* 2,000 feet of copper wire .1 inch diameter will have 2 ohms resistance; 10,000 feet, 10 ohms, etc. Law II, Fig. 102.

III. *The resistance of a conductor is inversely proportional to its cross-sectional area, and in the case of round wire inversely proportional to the square of the diameter.* Area varies directly as the diameter squared, or area varies as d^2 (see note below). A wire one-half inch in diameter has four times as great a resistance as a wire one inch in diameter, because as the area increases the resistance decreases. For example: No. 24 (B. & S.) wire has a diameter of .02 inch, and No. 30 has a diameter of .01 inch, or one-half the diameter of No. 24; 39 feet of No. 24 has a resistance of one ohm, and 9.75 feet of No. 30 equals one ohm (which is nearly $\frac{39}{2^2} = \frac{39}{4} = 9.75$). Law III, Fig. 102.

The area of a circle varies directly as the square of its diameter and is equal to $\frac{3.1416}{4} \times$ diameter squared or $.7854 \times d^2$. For example a wire 1 inch in diameter has an area of $1 \times 1 \times .7854 = .7854$ inches, while the area of a wire 2 inches in diameter equals $2 \times 2 \times .7854 = 3.1416$ inches. Thus the second wire has twice the diameter of the first wire, and *not only twice but four times* the area of the first wire. The areas of round wires vary directly as the squares of their diameters.

IV. *The resistance of a conductor of given length and cross-section depends upon the material of which it is made.* For example, the resistance of 1,000 feet of copper wire $\frac{1}{10}$ inch diameter (No. 10 B. & S.) is about 1 ohm, while the resistance of a piece of iron wire of the same length and cross-section is about 6.3 ohms, and a similar piece of German silver 12.8 ohms. Law IV, Fig. 102.

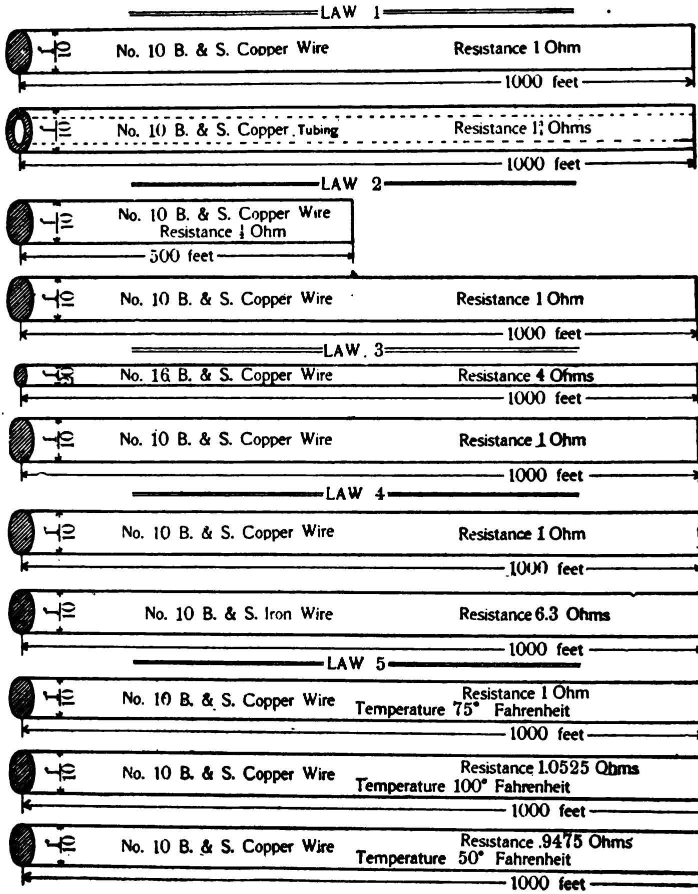


Fig. 102.—Laws of Resistance for Electrical Conductors.

V. *The resistance of a conductor depends upon the temperature and is affected by any other cause which modifies its molecular condition.* The comparative resistances of the copper, German silver, etc., in Law IV, are only true for a definite temperature. If these substances are heated the resistance of the copper is increased nearly 10 times as much as that of the German silver, and 20 times as much as an alloy called platinoid. Law V, Fig. 102.

All metals have their resistance increased by an increase of temperature. Carbon and all electrolytic conductors (battery solutions) decrease in resistance as the temperature increases. The resistance of copper increases about one-quarter of one per cent (.0021) for each degree temperature rise, *Fahrenheit* scale. See ¶ 262. The *hot* resistance of the carbonized filament of an incandescent lamp is about one-half the *cold* resistance.

VI. *The resistance of a conductor is always constant at the same temperature, irrespective of the strength of current flowing through it, or the electromotive force of the current.* If a conductor offers 5 ohms to a current of one ampere, it offers the same amount to a current of 10 amperes (provided the temperature is constant).

128. Calculation of Resistance.—One foot of copper wire $\frac{1}{1000}$ inch diameter has a resistance of 10.79 ohms at 75° Fahrenheit. Ten feet will have 107.9 ohms. One foot of copper wire $\frac{2}{1000}$ inch diameter will have one-fourth the resistance, ($\frac{1}{d^2}$ or $\frac{1}{2^2}$) or 10.79 divided by $4 = 2.69$ ohms. If this last wire were iron it would have 6.3 times the resistance, or 16.947 ohms. *Resistance varies directly as the length, inversely as the cross-sectional area, and with the material of the conductor.*

Let R represent resistance in ohms;
L " length in feet;
D " diameter (expressed in thousandths of an inch)
K " resistance of 1 foot .001 inch diameter.

Then by above statement:

$$\text{Resistance} = K \times \frac{\text{Length}}{\text{d (squared)}},$$

$$\text{or } R = \frac{K \times L}{d^2} \quad \ldots\ldots \quad (16).$$

Prob. 14: Find the resistance of 1000 feet of *copper* wire .1 inch in diameter.

By Formula (16) $R = \frac{K \times L}{d^2}$.

K for copper = 10.79.

.1 inch = 100 thousandths = 100 mils.

Substituting,

$$R = 10.79 \times \frac{1000}{100 \times 100} = 1.079 \text{ ohms.}$$

The value of K is constant for the same wire, but different for each metal, and for copper at 75° Fahr. it is 10.79 ohms (K). The value of K for other metals can be taken from the table below, and the resistance of any wire can be calculated when its dimensions are known. The resistance obtained corresponds with the temperature for which K is given. The following table gives the resistance of a foot of wire, .001 inch diameter, or the values of K for different metals when the temperature is 68° Fahr. See ¶ 262. K therefore is the resistance of 1 mil-foot.

Table VI.—Resistances of a Mil-Foot of the Metals (Values of K).

Silver, 9.84	Zinc, 36.69	German Silver, 128.29
*Copper, 10.79	Platinum, 59.02	‡Platinoid, 188.93
†Aluminum, 17.21	Iron, 63.35	Mercury, 586.24

Prob. 15: Substitute an iron wire for the copper wire in Prob. 14, and find its resistance.

By Formula (16) $R = \frac{K \times L}{d^2}$.

Substituting,

$$R = 63.35 \times \frac{1000}{100 \times 100} = 6.335 \text{ ohms.}$$

K for iron = 63.35.

Iron has thus about six times the resistance of copper.

129. Wire Measure.—The Circular Mil.—In wire measure a mil is one one-thousandth of an inch ($\frac{1}{1000}$, or .001 inch, or 1 mil). The area of a round wire 1 mil in diameter is 1 circular mil. If the wire is 2 mils in diameter ($\frac{2}{1000}$, or .002 inch, or 2 mils), then it has a circular mil area of 4 circular mils, the result being obtained by expressing the diameter of the wire in mils and squaring it (multiplying it by itself). The circular mil is used as the unit of area in the calculation of *round* wires for electrical purposes (the square mil for rectangular wires). It is the area of a circle having

*10.79, or (10.8) is generally used in practice as the value of K, for *commercial* copper at the average working temperature of 75° F.

† Value for annealed aluminum (conductivity 54).

‡ German silver 49 parts, tungsten 1 part.

a diameter of $\frac{1}{1000}$ inch; hence the square of any diameter, expressed in thousandths of an inch, will give as a product the number of circular units that can be placed side by side in a square, the sides of which are equal to the diameter that has been squared, the united area of the small circles contained within such a square being equal to the area of the large circle. This is illustrated in Fig. 103, where the large circle represents a wire three mils in diameter, and the small circles are the circular mils (9) whose united areas equal the area of the large circle One circular mil equals .000000785 square inch.

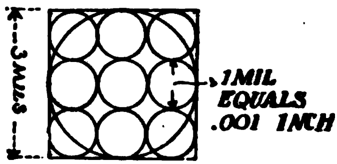


Fig. 103.—Area of the Large Circle Equals 9 Circular Mils.

1.—TO FIND THE CIRCULAR MIL AREA OF ANY ROUND WIRE WHEN ITS DIAMETER IN INCHES IS KNOWN:

Express the diameter as a whole number in mils and square it.

Let d = diameter;
d^2 = diameter squared;
C. M. = circular mil area.

Then,

$$C.\,M. = d^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (17).$$

Prob. 16: What is the circular mil area of a wire ¼ inch diameter?

$$1 \text{ inch} = \frac{1000}{1000};\ \text{therefore, } \tfrac{1}{4} \text{ inch} = \frac{250}{1000} \text{ or } 250 \text{ mils.}$$

By Formula (17) $C.\,M. = d^2 = d \times d = 250 \times 250 = 62500$ C. M.

2.—TO FIND THE DIAMETER OF ANY WIRE WHEN THE CIRCULAR MIL AREA IS KNOWN:

Extract the square root of the circular mil area. The result is the diameter expressed in mils,

$$\text{or } d = \sqrt{C.\,M.} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (18).$$

Prob. 17: What is the diameter of a wire if the area is 6530 C. M. (No. 12 B. & S.)?

By Formula (18) $d = \sqrt{C.\,M.} = \sqrt{6530} = 81$ mils nearly, or 081 inch diam.

130. The Square Mil.—Circular mil area applies to round wires, and is nearly one-quarter (.2146) larger than the true square inch area of round wires. Many conductors

now used are rectangular in cross-sectional area, so that it is sometimes necessary to find their equivalent area in round wire measure. One square mil equals .000001 square inch.

3.—To find the area of a rectangular wire in square mils:

Express the dimensions in mils and find the product of the dimensions. **The result is square mils.**

$$\text{Let } c = \text{thickness (in mils)};$$
$$d = \text{width (in mils)}.$$

$$\text{Sq. mils} = c \times d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19).$$

Prob. 18: A copper ribbon for a field coil measures $\frac{5}{8}$ inch × $\frac{1}{8}$ inch. Find its square mil area.

$\frac{5}{8} = .625$, or 625 mils $\frac{1}{8} = .125$, or 125 mils.

By Formula (19) Sq. mils $= c \times d = 125 \times 625 = 78125$ sq. mils.

4.—To convert circular mil area into square mil area:

Multiply the circular mil area by .7854. **The result is square mils.**

$$\text{One circular mil} = .7854 \text{ square mil.}$$

Therefore,

$$\text{sq. mils} = \text{C. M.} \times .7854 \quad . \quad . \quad . \quad (20).$$

Prob. 19: What is the square mil area of a wire $\frac{1}{4}$ inch diameter?

By Prob. 16 its C. M. area was calculated to be 62500 C. M.

By Formula (20) Sq. mil area $=$ C. M. $\times .7854 = 62500 \times .7854 =$ 49087.5 sq. mils.

5.—To convert square mil into circular mil area:

Multiply the square mil area by 1.2732. **The result is circular mils.**

$$\text{One square mil} = 1.2732 \text{ mils.}$$

Therefore,

$$\text{C. M.} = \text{sq. mils} \times 1.2732 \quad . \quad . \quad (21).$$

Prob. 20: Find the circular mil area of the copper wire in Prob. 18

By Prob. 18 Sq. mil area $= 78125$.

By Formula (21) C. M. $=$ sq. mils $\times 1.2732 = 78125 \times 1.2732 =$ 99468.75 C. M.

131. The Wire Gauge.—A number of wire gauges, differing slightly from one another, have been originated by different manufacturers of wire, but the one generally used in this country is the B. & S. gauge (Brown & Sharpe Manufacturing Co.), commonly called the *American Gauge.* Tables of several other gauges will be found in the Appendix. Table VII gives the B. & S. gauge. The first column gives

Table VII.—Wire Table, Standard Annealed Copper at a temperature of 25° C (77° F.)

American Wire Gauge (Brown & Sharpe)

Gauge No	Diam. in Mils d	AREA Cir Mils d^2	WEIGHT Lbs. per 1000 ft.	Lbs. per ohm.	LENGTH Feet per lb.	Feet per ohm.	RESISTANCE Ohms per 1000 ft.	Ohms. per lb.
0000	460 0	211600.	640.5	12810.	1.561	20010.	0.04998	0.00007806
000	409.6	167800.	507.9	8057.	1.968	15870.	.06303	.0001217
00	364.8	133100.	402.8	5067.	2.482	12580.	.07947	.0001935
0	324.9	105500.	319.5	3187.	3.130	9979.	.1002	.0003138
1	289.3	83690.	253.3	2004.	3.947	7913.	.1264	.0004990
2	257 6	66370.	200.9	1260.	4.977	6276.	.1594	.0007934
3	229.4	52640.	159.3	792.7	6.276	4977.	.2009	.001262
4	204.3	41740.	126.4	498.6	7.914	3947.	.2534	.002006
5	181.9	33100.	100.2	313.5	9.980	3130.	.3195	.003189
6	162.0	26250.	79.46	197.2	12.58	2482.	.4029	.005071
7	144.3	20820.	63.02	124.0	15.87	1968.	.5080	.008064
8	128.5	16510.	49.98	77.99	20.01	1561.	.6406	.01282
9	114.4	13090.	39.63	49.05	25.23	1238.	.8078	.02039
10	101.9	10380.	31.43	30.85	31.82	981.8	1.019	.03242
11	90.74	8234.	24.92	19.40	40.12	778.5	1.284	.05155
12	80.81	6530.	19.77	12.20	50.59	617.4	1.620	.08198
13	71.96	5178.	15.68	7.673	63.80	489.6	2.042	.1303
14	64.08	4107.	12.43	4.826	80.44	388.3	2.576	.2072
15	57.07	3257.	9.858	3.035	101.4	307.9	3.248	.3295
16	50.82	2583.	7.818	1,909	127.9	244.2	4.095	.5239
17	45.26	2048.	6.200	1.200	161.3	19.37	5.164	.8330
18	40.30	1624.	4.917	0.7549	203.4	153.6	6.512	1.325
19	35.89	1288.	3.899	.4748	256.5	121.8	8.210	2.106
20	31.96	1022.	3.092	.2986	323.4	96.59	10.35	3.349
21	28.46	810.1	2.452	.1878	407.8	76.60	13.06	5.325
22	25.35	642.4	1.945	.1181	514.2	60.74	16.46	8.467
23	22.57	509.5	1.542	.07427	648.4	48.17	20.76	13.46
24	20.10	404.0	1.223	.04671	817.7	38.20	26.18	21.41
25	17.90	320.4	0.9699	.02938	1031.	30.30	33.01	34.04
26	15.94	254.1	.7692	.01847	1300.	24.02	41.62	54.13
27	14.20	201.5	.6100	.01162	1639.	19.05	52.48	86.07
28	12.64	159.8	.4837	.007307	2067.	15.11	66.18	136.8
29	11.26	126.7	.3836	.004595	2607.	11.98	83.46	217.6
30	10.03	100.5	.3042	.002890	3287.	9.503	105.2	346.0
31	8.928	79.70	.2413	.001818	4145.	7.536	132.7	550.2
32	7.950	63.21	.1913	.001143	5227.	5.976	167.3	874.8
33	7.080	50.13	.1517	.0007189	6591.	4.739	211.0	1391.
34	6.305	39.75	.1203	.0004521	8310.	3.759	266.1	2212.
35	5.615	31.52	.09542	.0002843	10480.	2.981	335.5	3517.
36	5.000	25.00	.07568	.0001788	13210.	2.364	423.0	5592.
37	4.453	19.83	.06001	.0001125	16660.	1.874	533.5	8892.
38	3.965	15.72	.04759	.00007074	21010.	1.487	672.7	14140.
39	3.531	12.47	.03774	.00004448	26500.	1.179	848.2	22480.
40	3.145	9.888	.02993	.00002798	33410.	9.9349	1070.	35740.

The *fundamental resistivity* used in calculating this table is the Annealed Copper Standard of the United States "Bureau of Standards," and is 0,15328 ohms (meter, gram) at 20° C. The *temperature coefficient* for this particular resistivity, is at 20° C=0.00393, or at 0°=.00427. Specific Gravity=8.89 per cubic centimeter. The values at 25° C (77° F.) were selected as being nearer the average working temperature, resistance per-mil-foot at this temperature is 10.58 ohms. (See foot-note page 110).
This table is intended as an ultimate reference table and is computed to a greater precision than is desired in practice.

the gauge number; for example, the scale in the B. & S. gauge is from No. 0000 (four naughts) wire (460 mils diam.)

to No. 40 (3 mils diam.), the sizes decreasing as the gauge numbers increase. The diameter, area, weight, length and resistance are also given for each size wire.

132. Wire Calculations.—Case 1.—Given Length and Area of Any Wire to Find Its Resistance:

The resistance of any wire is equal to its length multiplied by the resistance of a mil-foot (K) *and this product divided by its area.*

Let L = length of the wire (in feet);
R = resistance (in ohms);
C. M. = circular mil area (diam²);
K = resistance of one mil-foot.

Then,

$$R = \frac{K \times L}{C.\,M.} \quad \ldots\ldots\ldots\ldots \quad (22).$$

Prob. 21: A copper wire has a cross-sectional area of 8234 C. M. and is 1050 feet long. What is its resistance?

By Formula (22) $R = \frac{K \times L}{C.\,M.}$. K for copper = 10.79.

$$R = \frac{10.79 \times 1050}{8234} = 1.37 \text{ ohms.}$$

L = 1050 feet. C. M. = 8234.

Case 2.—Given Resistance and Area to Find the Length:

The length of any wire is equal to its resistance, multiplied by its circular mil area, and this product, divided by the resistance of a mil-foot (K).

$$L = \frac{R \times C.\,M.}{K} \quad \ldots\ldots\ldots\ldots \quad (23).$$

Prob. 22: What is the length of German silver wire wound on a resistance spool, if its resistance is 500 ohms and the size of wire No. 20 B. & S.?

By Formula (23) $L = \frac{R \times C.\,M.}{K} = \frac{500 \times 1022}{128.29} = 3983\ 16$ feet.

R = 500 ohms, C. M. = 1022, K = 128.29.

No. 20 B. & S. = 1022 mils (from Table VII). K for German silver = 128.29 (from Table VI).

Case 3.—Given Length and Resistance to Find the Area:

The area in circular mils of any wire is equal to its length multiplied by the resistance of a mil-foot (K) *and this product divided by its resistance.*

$$C.M. = \frac{L \times K}{R} \quad \dots \dots \dots \dots \dots \quad (24).$$

Prob. 23: What is the circular mil area of 1,000 feet of a certain iron wire, if its resistance is 30 ohms?

By Formula (24) $C.M. = \frac{L \times K}{R} = \frac{1000 \times 63.35}{30} = 2111.6$ C. M.

K for iron = 63.35 from Table VI.
L = 1000 feet, R = 30 ohms, K = 63.35.

Case 4.—Given the Area to Find the Weight.

The weight per mile (5280 feet) *of any bare copper wire is equal to the area in circular mils divided by the constant 62.5.* Copper wire weighs about 555 pounds per cubic foot; iron wire weighs about 480 pounds per cubic foot.

$$\text{Pounds per mile (bare copper wire)} = \frac{C.M.}{62.5} \quad \dots \quad (25).$$

$$\text{Pounds per foot (bare copper wire)} = \frac{C.M.}{62.5 \times 5280} \quad (26).$$

$$\text{Pounds per mile (bare iron wire)} = \frac{C.M.}{72.13} \quad \dots \quad (27).$$

Prob. 24: The circular mil area of a No. 10 B. & S. wire is 10,380. How many pounds of bare copper wire will be required for two lines running a distance of 5 miles?

By Formula (25) lbs. per mile $= \frac{C.M.}{62.5} = \frac{10380}{62.5} = 166.08$ lbs. per mile.

$166.08 \times 5 \times 2 \quad 1660.8$ lbs.

133. Specific Resistance, Relative Resistance and Conductivity of Metals.—In comparing different materials, some standard of unit dimensions must be adopted. The commercial copper wire standard generally used, until the Annealed Copper Standard (page 113) was recommended by the United States Bureau of Standards, was Matthiessen's Standard, having a specific resistance of 1.594 microhms per cubic centimeter at the standard temperature of 0° Centigrade. In scientific writings, *specific resistance* is usually given as the resistance between two opposite faces of a cube of the material at 0° C., instead of on the basis of a wire one foot long and one mil in diameter, which is generally used in practice. The following (Table VIII) gives the specific resistance for a centimeter cube and an inch cube of the materials, also the relative resistance and conductivity. Silver, the best conductor, has a conductivity 100%.

Table VIII.—Specific Resistance, Relative Resistance and Conductivity of Conductors.

Referred to Matthiessen's Standard.

Metals	Resistance in Microhms at 0° C.		Relative Resistance %	Relative Conductivity %
	Centimeter Cube	Inch Cube		
Silver (annealed)	1.47	.579	92.5	108.2
Copper (annealed)	1.55	.610	97.5	1.2.6
Copper (Matthiessen's Standard)	1.594	.6276	100	100.0
Gold (99.9% pure)	2.20	.865	138	72.5
Aluminum (99% pure)	2.56	1.01	161	62.1
Zinc	5.75	2.26	362	27.6
Platinum (annealed)	8.98	3.53	565	17.7
Iron	9.07	3.57	570	17.6
Nickel	12.3	4.85	7,778	12.9
Tin	13.1	5.16	828	12.1
Lead	20.4	8.04	1,280	7.82
Antimony	35.2	13.9	2,210	4.53
Mercury	94.3	37.1	5,930	1.69
Bismuth	130.0	51.2	8,220	1.22

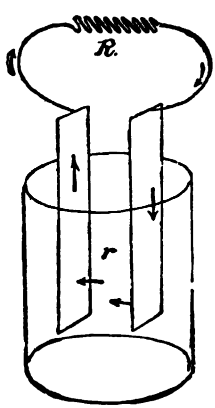


Fig. 104.—The Internal and External Resistance of a Cell.

134. Internal Resistance of a Battery.—Resistance in a voltaic circuit may be divided into two parts: *internal resistance* (r), which the current encounters in passing through the liquid from one plate to the other, and *external resistance* (R), or that of the outer circuit. See Fig. 104. The current that a cell will give, therefore, depends upon its internal resistance, and will be greater the less this resistance, and *vice versa*. The internal resistance is governed by the same laws as the external resistance. Thus:

$$r \text{ (internal resistance)} = K \times \frac{\text{distance of plates apart} \quad (L)}{\text{areas of plates submerged} \quad (d^2)}$$

or the internal resistance varies with

(1) The electrolyte used,
(2) Distance of plates apart,
(3) Size, or area of plates.

A good battery, therefore, should **have a low internal resistance.**

QUESTIONS.

1. The conductivity of a porcelain rod is very low. How will this affect its insulating qualities?
2. What is the function of an insulator?
3. The resistance of 5 pounds of No. 36 platinoid wire is very high. How does this affect the conductivity?
4. A battery sends 5 amperes through a piece of copper wire. Would the same cell send more or less current through another piece of copper wire twice as long but of double the area of the first piece?
5. If the second wire in question 4 was twice the length and twice the diameter of the first wire, what would be your answer?
6. Current from a cell flowing through a piece of iron wire deflects a galvanometer needle 40 degrees. When a piece of aluminum of similar dimensions to that of the iron is substituted, the deflection is 55 degrees. How do you account for this, since both wires are exactly the same size?
7. The resistance of an incandescent lamp is 500 ohms cold. Will it be more or less when the lamp is lighted? Why?
8. One mile of a certain iron wire has a resistance of 6 ohms. What will be the resistance of one-quarter of a mile of the same wire?

PROBLEMS.

1. The insulation of a wire measures 16.75 megs. What is its equivalent resistance in ohms? *Ans.* 16,750,000 ohms.
2. What is the circular mil area of a wire $\frac{3}{16}$ inch in diameter? *Ans.* 35156 C. M.
3. The circular mil. area of a wire is 5625. What is its diameter? *Ans.* 75 mils.
4. An armature is wound with copper bars $\frac{3}{16}$ by $\frac{3}{8}$ of an inch. What is their equivalent area in circular mils? *Ans.* 89522 C. M.
5. The resistance of the series coil of a dynamo is .0065 ohm. Express its resistance in microhms. *Ans.* 6500 microhms.
6. What is the square mil area of a No. 12 B. & S. copper wire? *Ans.* 5128.662 sq. mils.
7. What is the resistance of 5 pounds of No. 18 B. & S. wire, allowing 5 per cent for insulation? *Ans.* 6.251 ohms.
8. The coils of a rheostat, constructed of No. 8 iron wire, have a resistance of 10 ohms. What length of wire was required? *Ans.* 2606.14 feet.
9. A rectangular wire has a square mil area of 20616.75. What is the equivalent circular mil area? *Ans.* 26249 C. M.
10. What size of B. & S. wire has an equivalent area to the wire in Prob. 9? *Ans.* No. 6.
11. Calculate the resistance of 2000 feet of No. 6 B. & S. copper wire. *Ans.* 0.822 ohms.
12. Construct from your *own calculations* by the use of formulæ a wire gauge table for No. 12 B. & S. copper wire. Give circular mil area, square mil area, pounds per mile, pounds per foot, pounds per ohm, feet per pound, feet per ohm, ohms per pound and ohms per foot.

LESSON XIII.

OHM'S LAW AND BATTERY CONNECTIONS.

Electromotive Force (Pressure)—Table IX. Electromotive Forces of Batteries and Dynamos—Ohm's Law—Ohm's Law Applied to a Battery Circuit—Methods of Varying Current Strength—The Size of a Cell—Cells Connected in Series to Increase the E. M. F.—Cells connected in Parallel or Multiple for Quantity—The Internal Resistance of Cells in Series—Current from Cells in Series—The Internal Resistance of Cells in Parallel or Multiple—Current from Cells in Parallel or Multiple—Advantage of Parallel Connection—Advantage of Series Connection—Cells Grouped in Multiple Series—Internal Resistance of Any Combination of Cells—Current Strength from Any Combination of Cells—Cells Connected in Opposition—Questions and Problems.

135. Electromotive Force (Pressure).

Exp. 41: Connect a Daniell cell in series with spool 4 of resistance spool set, ¶ 124, and a detector galvanometer, and note the value of the deflection. Now substitute a bichromate cell for the Daniell cell, using the same spool, and the deflection is greater than before. The E. M. F. of the bichromate cell is higher than that of the Daniell cell, and therefore causes a larger current to flow through the same resistance. Any other type of cell used would cause more or less current to flow through the spool, depending upon its E. M. F. (pressure in volts).

In a battery, the E. M. F., which is the primary cause of the current, is dependent on the nature of the plates and the solution used, *but independent of their size or distance apart.*

In a dynamo the E. M. F. is set up by revolving a bundle of wires in a magnetic field, and depends upon the strength of the field, the number of wires revolved, and the speed.

136. Electromotive Force of Batteries and Dynamos.—The following table gives the electromotive forces of the different cells described in Lesson IX :

Table IX.—E. M. F. of Batteries.

Bunsen	1.75 to 1.95 volts.	Grove	1.75 to 1.95 volts
Chloride of Silver	1.1 "	Harrison	2.5 "
Daniell	.98 to 1.08 "	Leclanche type	1.4 to 1.6 "
Dry cell	1.4 "	Partz	1.95 to 2. "
Edison-Lalande	.7 "	Smee	.65 "
Grenet type	1.8 to 2.3 "	Storage battery	2.1 "

Dynamos generate from a few volts to thousands of volts, according to the purpose for which they are designed.

Incandescent lighting dynamos, direct current	125 volts
Alternating current dynamos, at brushes	100 to 2000 volts
Electric railway generators (direct current)	550 volts
Electroplating dynamos	2 to 6 volts
Magneto generators	700 to 2000 volts
Commercial power circuit generators	250 to 500 volts
Series arc light dynamos	2800 to 8000 volts

137. Ohm's Law.—IN ANY CIRCUIT THROUGH WHICH A CURRENT IS FLOWING WE HAVE THE THREE FOLLOWING FACTORS PRESENT: (1) THE **pressure** OR POTENTIAL DIFFERENCE, EXPRESSED IN **volts,** CAUSING THE CURRENT TO FLOW. (2) THE OPPOSITION OR **resistance** OF THE CIRCUIT, EXPRESSED IN **ohms,** WHICH MUST BE OVERCOME BEFORE THE CURRENT CAN FLOW. (3) THE **current strength,** EXPRESSED IN **amperes,** WHICH IS MAINTAINED IN THE CIRCUIT, AS A RESULT OF THE PRESSURE OVERCOMING THE RESISTANCE. A DEFINITE AND EXACT RELATION EXISTS BETWEEN THESE THREE FACTORS, PRESSURE, CURRENT STRENGTH, AND RESISTANCE IN ANY CIRCUIT, WHEREBY THE VALUE OF ANY ONE FACTOR MAY ALWAYS BE CALCULATED WHEN THE VALUES OF THE OTHER TWO FACTORS ARE KNOWN. THIS RELATION, KNOWN AS **Ohm's Law, is very important*,** SINCE IT FORMS THE BASIS FOR ALL CALCULATIONS IN ELECTRICAL ENGINEERING. IT MAY BE SUMMARIZED AS FOLLOWS:

First.—The current strength in any circuit is equal to the electromotive force applied to the circuit, divided by the resistance of the circuit.†

Let **E** = E. M. F., potential difference or available pressure, expressed in volts, applied to any circuit;

R = Resistance of the circuit, expressed in ohms;

I = Current strength, expressed in amperes, to be maintained through the circuit ‡. Then by the above statement

$$\textbf{Current} = \frac{\textbf{Pressure}}{\textbf{Resistance}},$$

$$\text{or}\quad \textbf{Amperes} = \frac{\textbf{Volts}}{\textbf{Ohms}},$$

$$\text{or}\quad I = \frac{E}{R} \quad \dots\dots\dots\dots \quad (28).$$

* Lesson XX is devoted to a further discussion of the practical application of Ohm's Law.

† Ohm's Law, as stated above, applies to direct currents flowing in any circuit. It is modified to some extent in alternating current calculations. See ¶ 297.

‡ C is used in some books as the symbol for current strength.

The following five statements and formulæ are directly derived from the above general statement of Ohm's Law, and are all therefore included in the expression $I = E \div R$.

Problems are solved under each case to illustrate the interpretation of each statement made.*

Prob. 25: An incandescent lamp has a resistance (hot) of 220 ohms, and is connected to an electric light main, across which 110 volts potential difference is maintained. What current will flow through the lamp?

By Formula (28) $I = \frac{E}{R} = \frac{110}{220} = \frac{1}{2}$ ampere.

$E = 110$ volts, $R = 220$ ohms.

Second.—*The current strength in any circuit increases or decreases directly as the E. M. F., or potential difference, increases or decreases, when the resistance is constant. With a constant pressure the current increases as the resistance is decreased, and decreases as the resistance is increased, or briefly, the current varies directly as the E. M. F. and inversely as the resistance.*

$I = \frac{E}{R}$, with R constant, I varies directly as E. With E constant the greater R, the less I, and *vice versa.*

Prob. 26: In Prob. 25, if the pressure is increased to 440 volts, what current will the lamp receive?

By Formula (28) $I = \frac{E}{R} = \frac{440}{220} = 2$ amperes.

$E = 440$ volts, $R = 220$ ohms.

This problem illustrates the increase of I with increase of E with a constant R.

Prob. 27: In Prob. 25, if the pressure is reduced to 55 volts, what current will the lamp receive?

By Formula (28) $I = \frac{E}{R} = \frac{55}{220} = \frac{1}{4}$ ampere.

$E = 55$ volts, $R = 220$ ohms.

This problem illustrates the decrease of I with the decrease of E when R is constant.

Prob. 28: In Prob 25 the voltage is again 110, but a lamp of 110 ohms resistance is used. What current will it receive?

By Formula (28) $I = \frac{E}{R} = \frac{110}{110} = 1$ ampere.

$E = 110$ volts, $R = 110$ ohms.

With E constant, I increases as R decreases.

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* Some problems refer to cells and circuits connected thereto, but the principles and connections are the same as those involved in direct current, electric lighting and power calculations. Problems on these subjects are given in later lessons.

Prob. 29: In Prob. 25 the pressure is 110 volts and another lamp of 440 ohms is used. What current will it receive?

By Formula (28) $I = \frac{E}{R} = \frac{110}{440} = \frac{1}{4}$ ampere.
$E = 110$ volts, $R = 440$ ohms.

Therefore, as R increases, when E is constant, I decreases.

Third.—*The electromotive force required to maintain a certain current strength in a circuit of known resistance, is numerically equal to the product of the current strength and the resistance* $E = I \times R$.

By the above statement,

Pressure = Current Strength × Resistance,
or **Volts = Amperes × Ohms,**
or $\mathbf{E = I \times R}$ . . . . **(29).**

Prob. 30: What pressure is required to cause 10 amperes to flow through an arc lamp if the resistance (hot) is 4.5 ohms?

By Formula (29) $E = I \times R = 10 \times 4.5 = 45$ volts.
$I = 10$ amperes, $R = 4.5$ ohms.

Fourth.—*The pressure varies directly as the current and resistance. For example, if a greater current is to be sent through the same resistance, a greater pressure must be applied; also, if the same current is to be passed through a higher resistance a greater pressure must be applied.* $E = I \times R$.

Prob. 31: What pressure is required to cause 15 amperes to flow through the lamp in Prob. 30?

By Formula (29) $E = I \times R = 15 \times 4.5 = 67.5$ volts.
$I = 15$ amperes, $R = 4.5$ ohms.

Prob. 32: If the lamp in Prob. 30 had a resistance of 9 ohms, what pressure must have been applied to have 10 amperes flow through it?

By Formula (29) $E = I \times R = 10 \times 9 = 90$ volts.
$I = 10$ amperes, $R = 9$ ohms.

Problems 31 and 32 illustrate how E increases directly with R and I. If either R or I had been decreased E would have been decreased also.

Fifth.—*The resistance required to be inserted in any circuit, so that a given current will flow by reason of a known pressure, is equal to the pressure to be applied, divided by the current strength that is to be maintained.* $R = \frac{E}{I}$

By the above statement,

$$\text{Resistance} = \frac{\text{Pressure}}{\text{Current strength}},$$

$$\text{or} \quad \text{Ohms} = \frac{\text{Volts}}{\text{Amperes}},$$

$$\text{or} \quad R = \frac{E}{I} \quad \ldots\ldots\ldots \quad (30).$$

Prob. 33: An electric heater is constructed of No. 18 iron wire and sufficient heat is radiated when the wire carries 10 amperes. The heater is placed across 110 volts. What will be the value of its hot resistance?

By Formula (30) $R = \frac{E}{I} = \frac{110}{10} = 11$ ohms (hot).
$E = 110$ volts, $I = 10$ amperes.

Sixth.—*The resistance required for any circuit varies directly with the pressure applied, and inversely as the value of the current to be maintained.* For example, with a *constant pressure* the resistance must be halved if the current is to be doubled; on the other hand, with a *constant current* to be maintained in a circuit at double the pressure, the resistance must be doubled.

Prob. 34: In Prob. 33 the current required is 20 amperes and the pressure the same as there given. What will be the hot resistance required?

By Formula (30) $R = \frac{E}{I} = \frac{110}{20} = 5.5$ ohms.
$E = 110$ volts, $I = 20$ amperes.

Prob. 35: If the pressure is 220 volts in Prob. 33, what resistance will be required?

By Formula (30) $R = \frac{E}{I} = \frac{220}{10} = 22$ ohms.
$E = 220$ volts, $I = 10$ amperes.

Problems 34 and 35 illustrate the sixth statement made above.

138. Ohm's Law Applied to a Battery Circuit.—*When the total E. M. F. is used in Ohm's Law, the total resistance of the circuit must also be used in calculating the current strength.* For example, when an electromagnet of .4 ohm is connected to a cell of 2 volts E. M. F. the current through the spool will *not* be $E \div R$ or $2 \div .4 = 5$ amperes, as might first be supposed. It requires a certain portion of the 2 volts to cause the current to flow through the cell's internal resistance. *The internal resistance must be added to the external resistance to obtain the total resistance of the circuit, which is to be divided into the total pressure to obtain the current strength.* If the internal

resistance of the above cell is .6 ohm, then the total resistance is $.4 + .6 = 1$ ohm, and the current equals $E \div R = 2 \div 1 = 2$ amperes, or less than one-half of our first result.

Let R = the total external resistance of the circuit (in ohms);
r = the internal resistance of the circuit (in ohms).
Then R + r = total resistance of the circuit (external + internal).

Then Ohm's Law becomes,

$$I = \frac{E}{R + r} \quad \dots\dots\dots\dots \quad (31).$$

Small r represents the internal resistance, in ohms, of a cell, or the resistance of the windings of a dynamo, which would be the dynamo's internal resistance.

Prob. 36: If a bichromate cell, E. M. F. 2 volts, internal resistance .5 ohm, is connected to an electromagnet having a resistance of 1.5 ohms, what current will the magnet receive?

By Formula (31) $I = \frac{E}{R + r} = \frac{2}{1.5 + .5} = 1$ ampere.
$E = 2$ volts, $R = 1.5$ ohms, $r = .5$ ohm.

Ohm's Law applies *equally as well to any part of a circuit* as to the whole circuit. When applied to part of a circuit, *care must be exercised to use the value of the pressure applied to the resistance of that portion of the circuit considered, when* E *will still represent the volts applied and* R *the resistance* of the part of the circuit to which E is applied. When E is used as the total pressure, R, to correspond, must be the total resistance. When E is used as the pressure applied to part of a circuit, R must be the resistance of that part to which this pressure is applied. This double application of the law is illustrated in Probs. 36, 37, 38, and 39, which should be carefully studied.

Prob. 37: The E. M. F. of a cell is 2 volts, its internal resistance .5 ohm. A number of different resistance spools are joined together *in series* and connected to the cell. By electrical measurement it is found that the pressure causing the current to flow through a .4 ohm spool is .6 volt. What is the value of the current flowing through this spool? Make a sketch of the circuit.

By Formula (28) $I = \frac{E}{R} = \frac{.6}{.4} = 1.5$ amperes.
$E = .6$ volt, $R = .4$ ohm.

Since the current is the same in all parts of a *series circuit*, 1.5 amperes must flow through each of the other spools men-

tioned; also through the internal resistance of the cell. This problem also illustrates the difference between E. M. F. and potential difference. See ¶ 70. The difference of potential, or pressure between the spool terminals, is .6 volt, while the E. M. F. is 2 volts. In Ohm's Law E represents either value. See ¶ 138, also Lesson XX.

Prob. 38: What portion of the total E. M. F. in Prob. 37 is used in overcoming the internal resistance of the cell?

By Formula (29) $E = I \times R$,

from which is derived $\mathbf{E = I \times r}$ . . . . **(32).**

This gives the pressure lost or volts drop inside the cell, ¶ 230.

By Formula (32) $E = I \times r = 1.5 \times .5 = .75$ volt.

$I = 1.5$ amperes, $r = .5$ ohm.

Prob. 39: What portion of the E. M. F. is available for the other spools in the series circuit of Probs. 37 and 38?

By Formula (30) $R = \frac{E}{I} = \frac{2}{1.5} = 1.333$ ohms $(R + r)$

$E = 2$ volts, $I = 1.5$ amperes.

Resistance of cell (.5) plus resistance of one spool (.4) = .9 ohm.

$1.333 - .9 = .433$ ohm for balance of spools.

By Formula (29) $E = I \times R = 1.5 \times .433 = .6495$ volt.

$I = 1.5$ amperes, $R = .433$ ohm.

From Formula (31) $I = \frac{E}{R + r}$ we may also change Formulæ (29) and (30) to include the internal resistance, as follows:

By Formula (29) $E = I \times R$.

Substituting $\mathbf{E = I \times (R + r)}$ . . . . **(33).**

By Formula (30) $R = \frac{E}{I}$;

substituting $(R + r) = \frac{E}{I}$;

by transposition $\mathbf{R = \frac{E}{I} - r}$ . . . . **(34).**

Also $\mathbf{r = \frac{E}{I} - R}$ . . . . **(35).**

Prob. 40: A cell with an internal resistance of 2 ohms sends a current of .035 ampere through the electromagnets of a bell having a resistance of 48 ohms. What is the E. M. F. of this cell?

By Formula (33) $E = I \times (R + r) = .035 \times (48 + 2) = .035 \times 50 = 1.75$ volts.

$I = .035$ ampere, $R = 48$ ohms, $r = 2$ ohms.

Prob. 41: A current of .25 ampere is maintained through a circuit by an E. M. F. of 2 volts; the internal resistance of the cell is 1.5 ohms. What is the value of the external resistance?

By Formula (34) $R = \frac{E}{I} - r = \frac{2}{.25} - 1.5 = 6.5$ ohms.

$E = 2$ volts, $I = .25$ ampere, $r = 1.5$ ohms.

139. Methods of Varying Current Strength. -- By Ohm's Law the current through any circuit may be regulated in two ways since $I = E \div R$; by increasing the pressure, E (the dividend), or by decreasing the resistance, R (the divisor), the current strength, I (the quotient) will be increased; or by decreasing the pressure, or increasing the resistance the current will be decreased. For example, 25 volts will cause 5 amperes to flow through 5 ohms. $I = E \div R$. If the pressure is raised to 35 volts the current strength will be 7 amperes. Current from any cell may thus be *decreased* by inserting resistance in the cell circuit. If sufficient current, however, cannot be obtained from a cell, and as the E. M. F. is a fixed quantity for each type of cell, the E. M. F. may be increased by joining two or more cells together, so that the total E. M. F. is the sum of the E. M. F.'s of the separate cells. This will be better understood from the hydraulic analogies in ¶ 141.

140. The Size of a Cell.—It has been stated that the E. M. F. of a cell is the same for the same type of cell, without regard to size, but that the current depends on the size. In Fig. 105 the cylindrical tank, A, has a capacity of 100 gallons of water under a pressure of 10 pounds per square inch due to the weight of the piston. Neglecting the weight of the water, the pressure gauge will record a pressure of 10 pounds. When the valve is opened the water will be discharged at the rate of about one gallon per minute, under a pressure of 10 pounds per square inch, so that at this rate it will require 100 minutes to empty the tank.

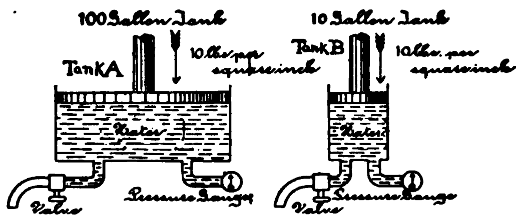


Fig. 105.—Two Cylindrical Tanks of Different Capacities, Containing Water Under Pressure.

A similar tank, B, has a capacity of 10 gallons of water under a pressure of 10 pounds per square inch, due to the piston. Neglecting the weight of the water, the pressure gauge will record 10 pounds also. The diameter of the pipe is the same size as in tank A, and when this valve is opened the water will flow out at the rate of one gallon per minute under a pressure

of 10 pounds per square inch as before, thus requiring only ten minutes to empty tank B. In both tanks the pressure and the rate of flow are the same, but tank A will maintain the current of water ten times as long as tank B. Now consider Fig. 106, in which the large cell A has a capacity of 100 ampere-hours (see ¶ 117) and an E. M. F. of 2 volts. When the switch is closed the galvanometer indicates, say 45 deflections, corresponding to a current strength of one ampere, and sufficient chemicals and zinc are present to maintain this current for 100 hours when the pressure is 2 volts and the rate of flow one ampere. Consider now a similar small cell B, which has a capacity of 10 ampere-hours and an E. M. F. of 2 volts. When the switch is closed through the same galvanometer the deflections are 45, as before, corresponding to a current strength of one ampere, sufficient chemicals and zinc being present to maintain this current for only 10 hours when the pressure is 2 volts and the rate of flow one ampere (neglecting the internal resistance). Thus the quantity of electricity depends on the size of the cell. If a large drain pipe had been used in tanks A and B, they would have been emptied more rapidly since the rate of flow would have been greater. If a galvanometer wound with a larger wire had been used, the cells A and B would not have maintained the current for so long a time, the rate of flow being greater.

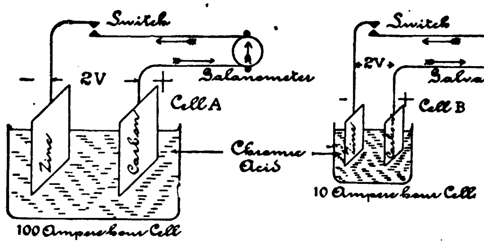


Fig. 106.—Two Cells of Different Size but Having the Same E. M. F.

141. Cells Connected in Series to Increase the E. M. F.—Consider the hydraulic analogy in Fig. 107, where the two similar cylindrical tanks A and B have a capacity of 100 gallons each. The pressure on the water in tank A and connecting pipe C is 10 pounds per square inch, due to the weight of the piston, so that the pressure gauge No. 1 indicates 10 pounds per square inch. In tank B the pressure on the water is 10 pounds per square inch, due to the pressure of

the piston on tank A above it, plus 10 pounds per square inch, due to the weight of its own piston, so that gauge 2 will register 20 pounds per square inch. The weight of the water is neglected. When the valve in the drain pipe of tank B is opened this tank will deliver the same quantity of water (100 gallons) as would be delivered by tank A, but at double the pressure. The rate of flow is, therefore, twice as rapid. If a number of similar tanks were connected in like manner above A, the pressure on gauge 2 would be increased 10 pounds per square inch for each tank added, although the quantity of water delivered through the valve would be the same as that of one tank. Consider now Fig. 108, where two cells, each having a capacity of 100 ampere-hours, and an E. M. F. of 2 volts are joined together so that the E. M. F.'s are in the same direction. The carbon pole of the first cell is connected to the zinc pole of the second cell, and the two remaining + and — terminals connected to the galvanometer. *Cells connected in this manner are joined in series.* The total pressure applied to the galvanometer when the switch is closed is twice the pressure of one cell (neglecting internal resistance) or 4 volts. The total quantity of electricity that will pass through the galvanometer is the same as would be delivered by each cell separately, *100 ampere-hours*, although, since it is delivered at twice the pressure of a single cell, the rate of flow is twice as great as with one cell. When a number

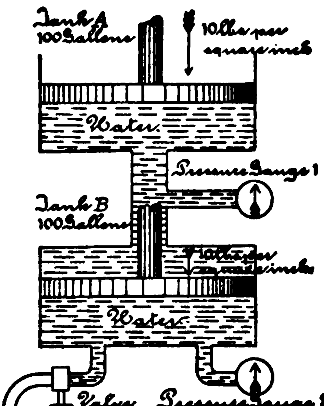


Fig. 107.—Two Cylindrical Tanks, Full of Water, Connected in Series for Pressure.

Gauge 2 records twice the pressure indicated upon gauge 1.

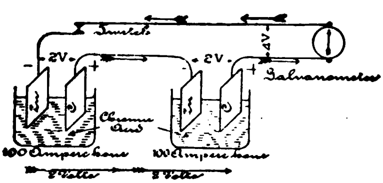


Fig. 108.—Two Cells Connected in Series for Pressure.

The galvanometer indicates twice the pressure of one cell.

of similar cells are thus connected in series the pressure applied to the galvanometer will be increased by 2 volts for each cell so added, but the total quantity of electricity that can be delivered will be equal to the capacity of only one cell.

142. Cells Connected in Parallel or Multiple for Quantity.—In Fig. 109, two similar cylindrical tanks have a capacity of 100 gallons of water each, and are connected by a pipe, C, in which a pressure gauge is attached. The piston in each tank exerts a pressure of 10 pounds per square inch, but the pressure gauge records only 10 pounds pressure, the same as though only one tank were used. The addition of any number of similar tanks will not increase the pressure, which will always remain 10 pounds per square inch.

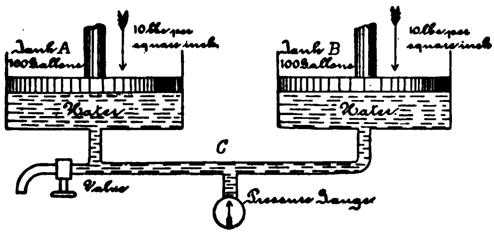


Fig. 109.—Two Cylindrical Tanks, Full of Water, Connected in Parallel for Quantity.

The pressure gauge records the pressure due to only one tank, but the quantity of water delivered is equal to the sum of the two capacities.

The weight of water is neglected. Although the pressure is not increased, the quantity of water which can be drawn from the valve in the drain pipe increases in proportion to the number of tanks so added; thus, the total capacity of 2 tanks is 200 gallons; 6 tanks, 600 gallons. In Fig. 107 the tanks were arranged in series to add their pressures together, while in this case the tanks are arranged in parallel to add their volumes together. In a cell, the total quantity of electricity depends upon the amount of zinc to be acted upon. Suppose the cell gives 1

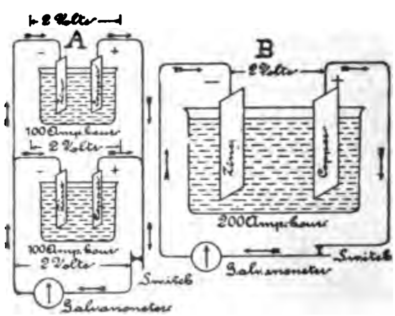


Fig. 110.—Two Cells Connected in Parallel for Quantity.

The total capacity and E. M. F. of the two small cells are exactly equal to that of the larger cell.

ampere-hour for each square inch of zinc exposed to the acid, then by increasing the area of the zinc plates a greater quantity of electricity can be obtained from the cell. This can be done in two ways: by making one very large cell, as B, Fig. 110, or by connecting the like plates of two or more smaller cells as in A, Fig. 110. Here the zinc plates of two cells are connected by a wire, forming one large zinc plate with double the area, the copper plates being similarly connected. *Cells so connected are arranged in parallel or multiple.* When the switch is closed in arrangement A the galvanometer is subjected to 2 volts pressure, neglecting internal resistance, which pressure would not be increased, no matter how many cells were thus connected. The total quantity of electricity that will flow through the galvanometer will increase in proportion to the number of cells so added. The two cells in A, therefore, could maintain 1 ampere through the galvanometer for 200 hours at a pressure of 2 volts, as could also the larger cell B. The advantage, then, of having small cells is that they can be arranged either for pressure or quantity, as may be desired, by connecting them in series or in multiple.

Exp. 42: Using a galvanometer of high resistance, compare the E. M. F.'s of different types of cells and record the deflections, the value of which will vary exactly as the E. M. F. varies.

Exp. 43: Connect unlike poles of two similar cells (which is termed joining cells in series) and attach the two remaining terminals to a high resistance galvanometer. The deflection is greater than with one cell, because the E. M. F.'s of the cells have been added together and greater pressure is applied to the galvanometer circuit. If the deflections are directly proportional to the current, their value will be nearly doubled. Add three similar cells in series and the pressure is three-fold, and so on.

Exp. 44: Connect two dissimilar cells in series (for example a Daniell cell, 1.1 volts, and Leclanche cell, 1. 5 volts) with a high resistance galvanometer, and the deflection is greater than with either cell alone. The pressure applied to the galvanometer is equal to the sum of the two pressures in series ($1.1 + 1.5 = 2.6$ volts).

Exp. 45: Record the deflections produced by one cell (say a Daniell) connected to a high resistance galvanometer. Using two similar cells, connect the positive poles by one wire, and the negative poles by another wire, and attach lead wires from these junctions to the galvanometer (when like poles are thus connected the cells are joined in *parallel* or *multiple*). The deflection is not perceptibly greater than with one cell, because the E. M. F. of two or more similar cells, joined in parallel, is the same as the E. M. F. of 1 cell; hence, two Daniell cells in parallel, 1 volt each, total E. M. F. 1 volt; 10 such cells in multiple, total E. M. F. 1 volt; 10 such cells in series, total E. M. F. 10 volts. In the above experiments a galva-

nometer of many turns of fine wire is used, so that little current will flow from the cells, and the deflections represent nearly the true pressure, ¶ 233.

143. The Internal Resistance of Cells in Series.—When a number of cells are connected in series, and to an external circuit, the current flowing through the external circuit must pass through each cell so connected, Fig. 111, requiring, therefore, a certain fraction of the total E. M. F. to overcome the resistance of each cell.

TO FIND THE TOTAL INTERNAL RESISTANCE OF A NUMBER OF SIMILAR CELLS CONNECTED IN SERIES:

Multiply the resistance of one cell by the number so connected.

Let r = internal resistance of 1 cell;
ns = *number* (n) of cells in *series* (s).
Then r × ns = total internal resistance of cells in series **(36)**.

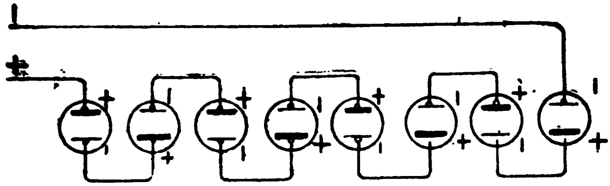


Fig. 111.—Eight Cells Connected in Series for Pressure.
The pressure is eight times that of one cell, as is also the total internal resistance.

Prob. 42: Ten Daniell cells, with an internal resistance of 2 ohms each, are connected in series. What is the total internal resistance?

By Formula (36) total r = r × ns = 2 × 10 = 20 ohms.
r = 2 ohms, ns = 10 cells.

144. Current from Cells in Series.—TO FIND THE CURRENT THAT WILL BE MAINTAINED IN AN EXTERNAL CIRCUIT FROM A NUMBER OF CELLS IN SERIES:

Find the total E. M. F. applied by multiplying the E. M. F. of 1 cell by the number connected in series. Find the total internal resistance by Formula (36). Then by Ohm's Law the Current equals the E. M. F. ÷ the total resistance.

Let E = E. M. F. of one cell;
r = internal resistance of one cell;
ns = number of cells in series;
R = external resistance.

Then $$I = \frac{E \times ns}{(r \times ns) + R} \quad \ldots\ldots\ldots \quad (37).$$

Prob. 43: Ten Daniell cells are joined in series to two spools of wire in series, one 4 ohms, the other 6 ohms. E. M. F. of one cell = 1 volt; internal resistance of one cell = 2 ohms. What current will flow through the circuit?

By Formula (37) $I = \frac{E \times ns}{(r \times ns) + R} = \frac{1 \times 10}{(2 \times 10) + 10} = \frac{10}{30} = \frac{1}{3}$ ampere.

$E = 1$ volt, $ns = 10$ cells, $r = 2$ ohms, $R = 6 + 4 = 10$ ohms.

145. The Internal Resistance of Cells in Parallel or Multiple.—When a number of similar cells are connected in multiple, Fig. 112, and to an external circuit, the total current flowing through the external circuit does not pass through the resistance of each cell as in the series case, but is divided among the cells in proportion to the number in parallel. The internal path for the total current is of much lower resistance

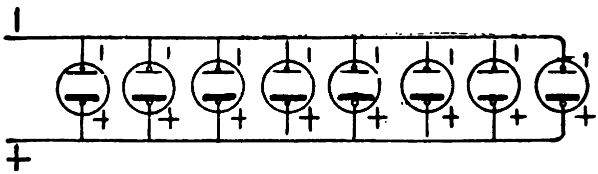


Fig. 112.—Eight Cells Connected in Parallel for Quantity.
The pressure is the same as that of one cell; the total internal resistance one eighth of that of one cell; the current nearly eight times that of one cell.

than the resistance of one cell. Cells connected in parallel have their like plates connected, Fig. 112, forming practically one large cell, the positive and negative plates of which are equal in area to the sum of the areas of the separate cells. The area of the conducting liquid is proportionately increased, and consequently, the internal resistance decreased. (See ¶ 134.)

TO FIND THE INTERNAL RESISTANCE OF A NUMBER OF CELLS IN PARALLEL:

Divide the resistance of one cell by the number connected in parallel.

Let r = the internal resistance of one cell;
nq = the number of cells in multiple or parallel.

Then $\frac{r}{nq}$ = *total internal resistance of cells in parallel* **(38).**

Prob. 44: In Prob. 43 the cells are joined in parallel. What is now the internal resistance?

By Formula (38) total internal resistance $= \frac{r}{nq} = \frac{2}{10} = \frac{1}{5}$ ohm.
$r = 2$ ohms, $nq = 10$ cells.

Exp. 46: Connect a very large Daniell cell to a *low resistance* galvanometer and record the deflections (say 60). Now join a much *smaller similar* cell to the same galvanometer and the deflections are much less (say 20). The pressure is the same in both cases, but the internal resistance of the small cell is higher, and since $I = E \div R + r$ (Formula 31), the current and the deflections must be less. Connect 3 of the smaller cells in parallel, Fig. 112, and to the galvanometer, and the deflections are now equivalent to the one large cell. The pressure is no higher since the cells are in parallel, therefore the total internal resistance of the three cells must be equal to the one large cell, since the current and pressure are the same.

146. Current from Cells in Parallel or Multiple.—TO FIND THE CURRENT THAT WILL BE MAINTAINED IN A CIRCUIT FROM A NUMBER OF SIMILAR CELLS JOINED IN PARALLEL :

Find the total internal resistance of the cells in parallel by Formula (38). Divide the E. M. F. of one cell by the sum of the external and internal resistances (according to Ohm's Law).

Let $E =$ E. M. F. of one cell;
$r =$ internal resistance of one cell;
$\frac{r}{nq} =$ total internal resistance of the cells in parallel;
$R =$ the total external resistance.

Then,

$$I = \frac{E}{\frac{r}{nq} + R} \quad \ldots\ldots\ldots \quad (39).$$

Prob. 45: Ten Daniell cells are joined in parallel and to an external resistance of 10 ohms. E. M. F. of 1 cell $= 1$ volt. Internal resistance of 1 cell $= 2$ ohms. Find the current through the external circuit.

By Formula (39) $I = \frac{E}{\frac{r}{nq} + R} = \frac{1}{\frac{2}{10} + 10} = .09$ ampere.

$E = 1$ volt, $r = 2$ ohms, $nq = 10$ cells, $R = 10$ ohms.

By comparison with Prob. 43, it will be noted that with this particular external resistance the series arrangement of the cells is much better, as nearly four times the current flows through the circuit when the cells are in series as when connected in multiple.

147. Advantage of Parallel Connection.—Cells are connected in parallel when it is desired to obtain the maximum

current through a low external resistance circuit, or when a small current is required for a long period of time. When so grouped the cells are equivalent to one very large cell, and are arranged to give a large quantity of electricity. When connected to a low external resistance, as compared with the internal resistance, the strength of current will also be large, while with a high external resistance the current will be small. The total quantity of electricity available from the supply of the chemicals can thus be used rapidly or slowly, as economy may demand. The following problems will illustrate this case:

Prob. 46: What current will flow through a resistance of .1 ohm from a Leclanche cell of 1.4 volts E. M. F. and an internal resistance of .4 ohm?

By Formula (31) $I = \frac{E}{R + r} = \frac{1.4}{.1 + .4} = 2.8$ amperes.

$E = 1.4$ volts, $R = .1$ ohm, $r = .4$ ohm.

Prob. 47: What will be the current in Prob. 46 with ten such cells in parallel?

By Formula (39) $I = \frac{E}{\frac{r}{nq} + R} = \frac{1.4}{\frac{.4}{10} + .1} = \frac{1.4}{.04 + .1} = 10$ amperes.

$E = 1.4$ volts, $r = .4$ ohm, $nq = 10$ cells, $R = .1$ ohm.

Prob. 48: Suppose the ten cells in Prob. 47 are connected in series What current will flow through the circuit?

By Formula (37) $I = \frac{E \times ns}{(r \times ns) + R} = \frac{1.4 \times 10}{.4 \times 10 + .1} = \frac{14}{4.1} = 3.41$ amperes.

$E = 1.4$ volts, $ns = 10$ cells, $r = .4$ ohm, $R = .1$ ohm.

The parallel grouping is therefore preferable in the above problems if the greatest possible current strength is desired in the external circuit.

148. Advantage of Series Connection.—A series grouping is employed when the external resistance is the principal one to be overcome and the maximum current strength is desired in the circuit. The advantage of this method will be shown by the following problems:

Prob. 49: A Leclanche cell, 1.4 volts and internal resistance of .4 ohm, is connected to an external resistance of 100 ohms. What current will flow through the circuit?

By Formula (31) $I = \frac{E}{R + r} = \frac{1.4}{100 + .4} = \frac{1.4}{100.4} = .01394$ ampere

$E = 1.4$ volts, $R = 100$ ohms, $r = .4$ ohm.

Prob. 50: Connect ten similar cells in parallel in Prob. 49 and find the current.

By Formula (39) $I = \frac{E}{\frac{r}{nq} + R} = \frac{1.4}{\frac{.4}{10} + 100} = \frac{1.4}{100.04} = .013994$ ampere.

$E = 1.4$ volts, $R = 100$ ohms, $r = .4$ ohm.

Ten cells so connected to this external resistance are, therefore, not much better than one cell. Compare with Prob. 44, where the external resistance was very low.

Prob. 51: Connect the cells in Prob. 50 in series and find the current strength.

By Formula (37) $I = \frac{E \times ns}{(r \times ns) + R} = \frac{1.4 \times 10}{(.4 \times 10) + 100} = \frac{14}{104} =$ .13 ampere.

$E = 1.4$ volts, $ns = 10$ cells, $r = .4$ ohm, $R = 100$ ohms.

With the cells in series ten times the current is passed through this resistance as when the cells are connected in parallel. In ¶ 146 the multiple combination proved to be best adapted for a particular circuit, while in this case the series grouping is desirable. The student should make a thorough comparison of the problems in ¶¶ 146 and 147.

149. Cells Grouped in Multiple-Series.—A combination of the series and multiple grouping of cells is sometimes desirable when a number of cells are available, to give either the maximum current through an external resistance, or to increase the capacity of the cells for maintaining a current in a circuit for a long period of time. For example 8 volts E. M. F. is required to light a small lamp, and 8 cells are available with an E. M. F. of 2 volts each. Arrange one group of 4 cells in series which will give the desired E. M. F., 8 volts*. Suppose this group would cause the lamp to burn 4 hours. Arrange a second group of 4 cells in series and join this group in multiple with the first group, Fig. 113. The total E. M. F. is still 8 volts, but with two groups in parallel

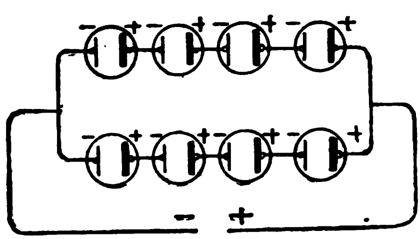


Fig. 113.—Multiple-Series Grouping of Cells. Four cells in series, two groups in parallel. Total E. M. F. equal to that of one group. Total internal resistance equal to one-half that of one group.

*Neglecting the internal resistance. See ¶ 226.

the quantity of electricity available has been doubled, so that the lamp will now burn 8 hours. Such a grouping of cells is called a *multiple-series* combination (practically a multiple of series). Two cells, each having an E. M. F. of 8 volts and an internal resistance of four times one of the above cells, could be placed in multiple and substituted for the 8 cells.

TO FIND THE CURRENT FROM A MULTIPLE-SERIES ARRANGEMENT OF CELLS JOINED TO AN EXTERNAL RESISTANCE :

Compute the E. M. F. and internal resistance of one group by Ohm's Law (Formula 37).

Consider the results as the data for one cell and then make calculations for the number of such cells (groups) *arranged in parallel* (by Formula 39).

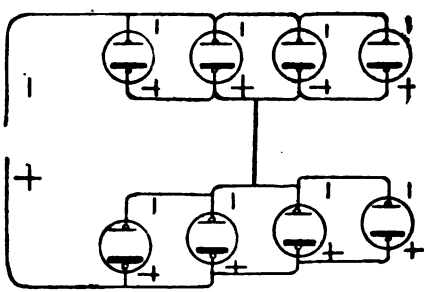


Fig. 114.—Series-Multiple Grouping of Cells. Four cells in parallel, two groups in series, equivalent to two cells in series and four groups in parallel.

Prob. 52: A multiple-series combination of 8 cells is joined to an external resistance of 3 ohms. The cells are arranged 4 in parallel, 2 groups in series, Fig. 114. Each cell has an E. M. F. of 2 volts and an internal resistance of .5 ohm. What current will flow through the external circuit?

E. M. F. of 1 group = 2 volts.

E. M. F. of 2 groups in series = $2 \times 2 = 4$ volts.

By Formula (38) Internal resistance of 1 group $= \frac{r}{nq} = \frac{.5}{4} =$ .125 ohm.

$E = 2$ volts, $nq = 4$ cells in 1 group, $r = .5$ ohm.

By Formula (36) Internal resistance of 2 groups in series $= r \times ns = .125 \times 2 = .25$ ohm.

r of 1 group = .125 ohm, ns = 2 groups.

By Formula (31) $I = \frac{E}{R + r} = \frac{4}{3 + .25} = 1.23$ amperes.

$R = 3$ ohms, r of 2 groups in series = .25 ohm; $E = 4$ volts, 2 groups in series.

150. Internal Resistance of any Combination of Cells.—

TO FIND THE INTERNAL RESISTANCE OF ANY MULTIPLE-SERIES COMBINATION OF CELLS :

Multiply the resistance of one cell by the number of cells in one

group and divide the product by the number of groups in multiple The number of cells in each group must be the same.

Let r = resistance of one cell;
ns = number of cells in series in one group;
nq = number of groups in parallel.
Total internal resistance of any combination of cells =

$$\frac{r \times ns}{nq} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40).$$

Prob. 53: Find the internal resistance of a combination of 24 cells arranged 6 in series, 4 groups in multiple. Each cell has a resistance of 4 ohms.

By Formula (40) Total resistance $= \frac{r \times ns}{nq} = \frac{4 \times 6}{4} = 6$ ohms.
$r = 4$ ohms, $ns = 6$ cells in one group, $nq = 4$ groups in multiple.

151. Current Strength from Any Combination of Cells. —TO FIND THE CURRENT THAT WILL BE MAINTAINED IN AN EXTERNAL CIRCUIT FROM ANY MULTLIPLE-SERIES COMBINATION:

Divide the total E. M. F. of one series group by the sum of the combined internal and external resistances.

Let I = Current in external circuit;
E = E. M. F. of one cell;
ns = number of cells in series in one group;
nq = number of groups in parallel;
r = internal resistance of one cell;
R = external resistance.
Then by Ohm's Law, Formulæ (37) and (39),

$$I = \frac{E \times ns}{\frac{ns \times r}{nq} + R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41).$$

Prob. 54: Find the current that would flow through an incandescent lamp, hot resistance 2 ohms, when connected to 24 cells arranged 4 in series and 6 in parallel. Each cell has an E. M. F. of 2 volts and an internal resistance of 3 ohms.

By Formula (41) $I = \frac{E \times ns}{\frac{ns \times r}{nq} + R} = \frac{2 \times 4}{\frac{4 \times 3}{6} + 2} = \frac{8}{4} = 2$ amperes.

$E = 2$ volts, $ns = 4$ cells in one group, $r = 3$ ohms, $nq = 6$ groups in parallel, $R = 2$ ohms.

152. Cells in Opposition.—When two cells are joined in parallel their E. M. F.'s are in opposition, since each one tends

to send a current through the other. If the E. M. F.'s are equal no current will flow through the connecting wires. Two equal forces, acting in direct opposition, produce equilibrium; if, however, the forces are unequal, then motion is produced in the direction of the greater force. For example, if the pressure acting downward on each piston in tank A and B, Fig. 109, is the same, no water will flow through the connecting pipe. Suppose the total downward pressure on A is 10 pounds and on B 30 pounds, then a current of water will flow from B to A, due to the difference in pressure between the opposing forces, 20 pounds (30 lbs. — 10 lbs). The piston at A will move upward. When two cells of unequal E. M. F.'s are connected in opposition a current will flow through the connecting wires and internal resistance in the direction of the higher E. M. F.

TO FIND THE CURRENT IN ANY CIRCUIT WHEN THE E. M. F.'S ARE IN OPPOSITION:

Divide the difference between the E. M. F.'s by the sum of the external and internal resistances.

The opposing E. M. F. is called the *Counter E. M. F.* and is usually represented by $\mathcal{E}$.

Formula (31) $I = \frac{E}{R + r}$ may include the above statement when expressed thus $I = \frac{E - \mathcal{E}}{R + r}$.

Prob. 54-A: Four Daniell cells, each having an E. M. F. of 1 volt and internal resistance of 2 ohms, are connected in series and in opposition to an accumulator having an E. M. F. of 2 volts and an internal resistance of .05 ohm. The resistance of the connecting wire is 0.2 ohm. What is the charging current?

By above Formula $I = \frac{E - \mathcal{E}}{R + r} = \frac{4 - 2}{.2 + (4 \times 2) + .05} = .24$ ampere.

E. M. F. $= E \times ns = 1 \times 4 = 4$ volts, $\mathcal{E} = 2$ volts, $r = r \times ns = 2 \times 4 = 8$ ohms $+ .05 = 8.05$ ohms, $R = .2$ ohm.

QUESTIONS.

1. An electromagnet connected to a Leclanche cell attracts many more filings than when it is connected to a Daniell cell. Why?
2. Upon what factors do the E. M. F.'s of a battery and dynamo depend?
3. An incandescent lamp receives insufficient current to properly illuminate it. Why is this, and what is necessary in order that it may burn at candle power?

4. A lamp requiring 4 volts is connected to two bichromate cells of 2 volts E. M. F. each, joined in series. It fails to light properly, though the E. M. F. of the two cells is 4 volts. Why is this?

5. A small size Daniell cell deflects a galvanometer 40 degrees, while a larger one of the same type produces 55 deflections. Why is this, since the E. M. F. of the cells is the same?

6. The cells in question 5, when connected to another galvanometer, both indicate the same deflection How do you account for this?

7. Two Partz cells are connected in series and to a large electromagnet; there are apparently no more filings attracted to the magnet than when one cell was used. If the iron is not nearly saturated, why is this, since the E. M. F. has been doubled?

8. Two Edison-Lalande cells are connected in parallel and to a galvanometer. The deflection is much greater than when only one cell was connected. Give reasons, since the E. M. F. is the same in both cases.

9. A Bunsen cell has an E. M. F. of 2 volts and an internal resistance of .4 ohm. Why will not this cell give 7 amperes through a very low external resistance?

10. If you are given the choice of two small Daniell cells or one large Daniell cell of twice the capacity of the small ones, which would you prefer? Why?

11. Would you connect two cells having an E. M. F. of 0.7 and 2.4 volts respectively in series? Give a reason for your answer.

12. Would you connect the cells mentioned in question 11 in parallel? Give reason for your answer.

13. The zinc rods of two Fuller cells are connected by a wire, and wires are led from the two carbon terminals to a galvanometer. The cells are in good condition and the connections tight, but the needle is not deflected. Give reason and illustrate your answer by a sketch.

14. If you are asked to select a good open circuit cell, what requirements should it fulfill?

15. The voltage applied to the terminals of a lamp is to be doubled, but the lamp must not receive any more current than before. Explain how this could be accomplished.

PROBLEMS.

1. What pressure must be applied to an incandescent lamp if it has a resistance of 55 ohms and requires 2.2 amperes? *Ans.* 121 volts.

2. A Daniell cell has an E. M. F. of 1 volt and an internal resistance of 2.2 ohms. What current will flow through an electromagnet connected to it, wound with 150 feet of No 18 B. & S. copper wire? *Ans.* 0.312 ampere.

3. The current through the field magnets of a dynamo is 2 amperes and the applied pressure 120 volts. What is the resistance of the circuit? *Ans.* 60 ohms.

4. The E. M. F. of a cell is 2.44 volts, its internal resistance .6 ohm, and it is connected to a circuit of 1.4 ohms. What pressure is required to send the current used through the battery? *Ans.* 0.732 volt.

5. A bell circuit is operated by 3 Leclanche cells in series. Each cell has an E. M. F. of 1.4 volts, and an internal resistance of .4 ohm. What current will the bell receive if its resistance, including the line, is 26 ohms? *Ans.* 0.198 ampere.

6. To operate a small motor 6 Grenet cells are connected in parallel. Each cell has an E. M. F. of 2 volts and an internal resistance of .6 ohm. The total external resistance is .9 ohm. What current will the motor receive? *Ans.* 2 amperes.

7. Some miniature incandescent lamps are lighted by 24 Edison-Lalande cells, arranged 4 in series and 6 groups in parallel. Each cell has an E. M. F. of .7 volt and an internal resistance of .15 ohm, and the external circuit has a resistance of .21 ohm. What current do the lamps receive? *Ans.* 9 amperes.

8. Four Leclanche cells, E. M. F. 1.4 volts each, and internal resistance of .4 ohm each, are to operate an electric gas igniting circuit of 15 ohms resistance. Would you connect the cells in series or in parallel? Prove your answer by calculation. *Ans.* 0.337 ampere.

9. Calculate the current from all symmetrical combinations of 6 cells connected to an external resistance of 2 ohms. Each cell has an E. M. F. of 1.4 volts and an internal resistance of .5 ohm. *Ans.* Series = 1.68 amperes; parallel = .67 ampere; 2 in series, 3 groups in parallel = 1.2 amperes; 3 in series, 2 groups in parallel = 1.52 amperes.

10. A Harrison cell E. M. F. 2.5 volts, internal resistance .4 ohm and a dry cell 1.5 volts and .6 ohm internal resistance are connected in parallel. What current will flow through the connecting wire? *Ans.* 1 ampere.

11. A Daniell cell, Grenet cell, and Leclanche cell having E. M. F.'s of 1.1, 2, and 1.4 volts and internal resistances of 2.0, 0.3, and 0.5 ohms respectively, are connected in series to a resistance of 3 ohms. What current flows through the external resistance? *Ans.* .77 ampere.

12. Eight cells are joined in series-multiple; 4 cells in multiple, 2 groups in series, Fig. 114. Each cell has an E. M. F. of 2 volts and an internal resistance of .5 ohm. The cells are connected to a small incandescent lamp having a hot resistance of .75 ohm. What current will the lamp receive? *Ans.* 4 amperes.

LESSON XIV.

CIRCUITS AND THEIR RESISTANCE.

Conductance of a Circuit—Resistances in Series—Equal Resistances in Parallel (Joint Resistance)—Unequal Resistances in Parallel—Conductivity Method for Conductors in Parallel—Resistances Joined in Multiple-Series—Division of Current in a Divided Circuit—Potential Difference in Multiple Circuits—Current in Branches of Multiple Circuits—Shunts—Rheostats—Resistance of Connections—Laboratory Rheostats—Table X. Resistance of Commercial Apparatus—Questions and Problems.

153. Conductance of a Circuit.—THE CONDUCTANCE OF A CIRCUIT IS THE RECIPROCAL OF ITS RESISTANCE. (The reciprocal of a number is the quotient obtained by dividing one by that number, as the reciprocal of $4 = \frac{1}{4}$; of $\frac{2}{3} = \frac{3}{2} = 1\frac{1}{2}$.) The unit of conductance is the *mho* (ohm spelled backward). A wire of 1 ohm resistance has a conductance of 1 mho; if of 2 ohms resistance, $\frac{1}{2}$ mho; 8 ohms resistance, $\frac{1}{8}$ mho; $\frac{2}{3}$ ohm resistance, $\frac{3}{2}$ or $1\frac{1}{2}$ mhos. The resistance of a circuit is the reciprocal of its conductance. A wire of 7 mhos conductance has $\frac{1}{7}$ ohm resistance. If in Ohm's Law, conductance is used instead of resistance, and K represents the conductance of a circuit in mhos.

Then,

$$I = E \times K;$$
$$E = \frac{I}{K};$$
$$K = \frac{I}{E} \quad \ldots\ldots\ldots\ldots (42).$$

154. Resistances in Series.—TO FIND THE TOTAL RESISTANCE OF A NUMBER OF RESISTANCES CONNECTED IN SERIES:

Find the sum of the resistances connected. In Fig. 115, A equals 40 ohms; B equals 160 ohms; total resistance equals $40 + 160 = 200$ ohms. The same current will flow through A as through B.

155. Equal Resistances in Parallel—Joint Resistance In Fig. 116 the two resistances, A and B, are connected in parallel, and then in series with the battery wires. If the resistance of A is equal to that of B, the conductance will also be equal and the current will divide, one-half flowing through A and the other half through B. Since the total area of the conducting circuit has been increased, the combined or *joint resistance* of A and B will be less than either resistance separately. If the resistance of A equals that of B then the area will have been doubled, and the joint resistance equal to one-half that of A or B. Thus A and B = 10 ohms each; joint resistance = $\frac{1}{2}$ of 10 or 5 ohms. With three equal resistances in parallel the joint resistance will be $\frac{1}{3}$ the value of one of the resistances.

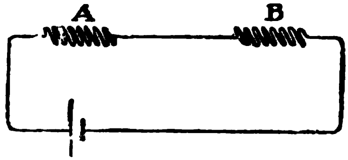


Fig. 115.—Two Unequal Resistances in Series.

TO FIND THE JOINT RESISTANCE OF ANY NUMBER OF EQUAL RESISTANCES CONNECTED IN PARALLEL:

Divide the value of a single resistance by the number connected in parallel.

Let R = a single resistance;
nq = number of equal resistances in parallel;
J. R. = joint resistance.

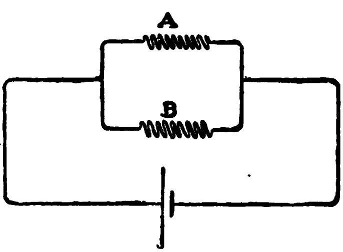


Fig. 116.—Two Equal Resistances in Parallel.

$$\text{Then, J. R.} = \frac{R}{nq} \quad . \; . \; . \; . \; . \quad (43).$$

TO FIND THE NUMBER OF EQUAL RESISTANCES CONNECTED IN PARALLEL (nq) WHEN THE JOINT RESISTANCE (J. R.) AND VALUE OF A SINGLE RESISTANCE (R) ARE KNOWN:

Divide the value of a single resistance by the joint resistance.

$$\text{Thus, nq} = \frac{R}{J.\,R} \quad . \; . \; . \; . \quad (44)$$

TO FIND THE VALUE OF A SINGLE RESISTANCE (R) WHEN THE JOINT RESISTANCE AND THE NUMBER OF EQUAL RESISTANCES IN PARALLEL ARE KNOWN:

Multiply the joint resistance by the number of equal resistances connected in parallel.

$$R = J.\ R. \times nq \qquad (45).$$

Prob. 55: Ten incandescent lamps are connected in parallel, Fig. 117. Each lamp has a resistance (hot) of 220 ohms. What is the total or joint resistance of the lamp circuit?

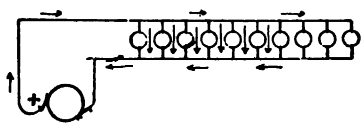


Fig. 117.—Ten Incandescent Lamps Connected in Parallel and to a Dynamo.

By Formula (43)

$$J.\ R. = \frac{R}{nq} = \frac{220}{10} = 22 \text{ ohms.}$$

$R = 220$ ohms, $nq = 10$ lamps in parallel.

Prob. 56: The joint resistance of 55 lamps connected in parallel is 4 ohms. What is the resistance of 1 lamp?

By Formula (45) $R = J.\ R. \times nq = 4 \times 55 = 220$ ohms.
$J.\ R. = 4$ ohms, $nq = 55$ lamps.

Prob. 57: The joint resistance of a number of electromagnets connected in parallel is 8 ohms and the resistance of 1 magnet, 40 ohms. How many magnets are connected?

By Formula (44) $nq = \frac{R}{J.\ R.} = \frac{40}{8} = 5$ electromagnets.
$R = 40$ ohms, $J.\ R. = 8$ ohms.

156. Unequal Resistances in Parallel.—In Fig. 118, two unequal resistances, 3 and 7 ohms respectively, are connected in parallel. The joint resistance will be less than either resistance considered separately.

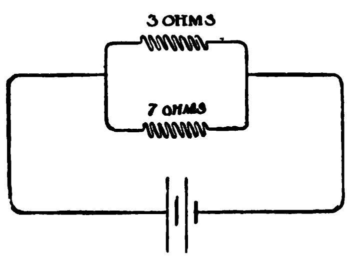


Fig. 118.—The Joint Resistance of Two Unequal Resistances in Parallel.

TO FIND THE JOINT RESISTANCE OF TWO UNEQUAL RESISTANCES CONNECTED IN PARALLEL:

Divide the product of the resistances by their sum.

Let R = first resistance;
R_1 = second resistance;
$J.\ R.$ = joint resistance.

Then the joint conductivity $= \frac{1}{R} + \frac{1}{R_1} = \frac{R_1 + R}{R \times R_1}$ mhos,

and the joint resistance $= 1 \div \frac{R_1 + R}{R \times R_1} = \frac{R \times R_1}{R + R_1}$ ohms,

$$\text{or J. R.} = \frac{R \times R_1}{R + R_1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (46).$$

Prob. 58: Find the joint resistance of two coils in parallel, having a resistance of 3 and 7 ohms respectively. Fig. 118.

By Formula (46) $\text{J. R.} = \frac{R \times R_1}{R + R_1} = \frac{3 \times 7}{3 + 7} = 2.1$ ohms.

$R = 3$ ohms, $R_1 = 7$ ohms.

IF MORE THAN TWO UNEQUAL RESISTANCES ARE CONNECTED IN PARALLEL:

First find the joint resistance of two wires, and considering this as a single resistance, combine it with a third resistance, and so on.

157. Conductivity Method for Conductors in Parallel. TO FIND THE JOINT RESISTANCE OF ANY NUMBER OF RESISTANCES CONNECTED IN PARALLEL:

Find the sum of the conductivities of the different paths through which the current flows and the joint resistance will be the reciprocal of the sum thus obtained.

Prob. 59: Find the joint resistance of 2 coils having 3 and 7 ohms resistance respectively, Fig. 118, by the conductivity method.

By ¶ 157 joint conductivity $= \frac{1}{3} + \frac{1}{7} = \frac{7 + 3}{21} = \frac{10}{21}$ mho.

Joint resistance $= \frac{21}{10} = 2.1$ ohms.

Compare with Problem 58.

Prob. 60: Find the joint resistance of 3 coils of wire having resistances of 2, 4 and 8 ohms respectively, Fig. 119.

By ¶ 157 joint conductivity $= \frac{1}{2} + \frac{1}{4} + \frac{1}{8} = \frac{4 + 2 + 1}{8} = \frac{7}{8}$ mho.

Joint resistance $= \frac{8}{7} = 1.142$ ohms.

158. Resistances Joined in Multiple-Series.—The same method of calculation is used as that already given for the internal resistance of cells, ¶ 145.

WHEN THE RESISTANCE OF ALL THE SERIES GROUPS ARE THE SAME:

Find the resistance of one group, and divide this sum by the number of groups in parallel.

WHEN THE GROUPS ARE OF UNEQUAL RESISTANCE: *Find the sum of the series resistances in one group, and treating this as a single resistance proceed as in ¶ 157.*

159. Division of Current in a Divided Circuit.—*The division of current in the branches of a multiple circuit is directly proportional to the conductance of the branches, or inversely proportional to their resistance.*

If A and B, Fig. 116, are equal in resistance and a current of 12 amperes flows from the battery, 6 amperes will flow through A, and 6 amperes through B. If A has a higher resistance than B (and consequently a lower conductance), then the greater portion of the current will flow through the lower resistance of B (which has a higher conductance.)

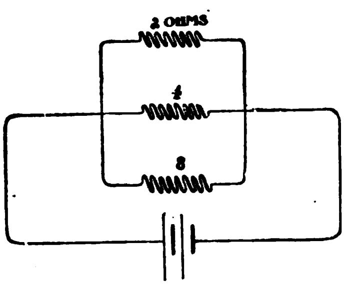


Fig. 119.—Three Unequal Resistances in Parallel.

If A has 2 ohms resistance and B 1 ohm, then *twice* as much current will flow through B as through A; or the current is divided into three parts, one-third of which flows through A and two-thirds through B. If the total current is 12 amperes, A then receives 4 amperes and B 8 amperes.

Prob. 61: A current of 39 amperes is passed through 3 coils of wire joined in multiple, Fig. 120, having the following resistances: A = 8, B = 12, and C = 16 ohms respectively. How many amperes will each coil receive?

By ¶ 157 joint conductance $= \frac{1}{8} + \frac{1}{12} + \frac{1}{16} = \frac{6+4+3}{48} = \frac{13}{48}$ mho.

The conductance of A $= \frac{6}{48}$ mho, of B $= \frac{4}{48}$ mho, and of C $= \frac{3}{48}$ mho.

Consider the current to divide into 13 parts (6 + 4 + 3), 6 parts of which pass through A, 4 through B, and 3 through C, or directly as their conductances.

Current through A $= \frac{6}{13}$ of 39 = 18 amperes;

B $= \frac{4}{13}$ of 39 = 12 amperes;

C $= \frac{3}{13}$ of 39 = 9 amperes.

Total current, ... 39 amperes.

160. Potential Difference in Multiple Circuits.—THE POTENTIAL DIFFERENCE REQUIRED TO BE MAINTAINED BETWEEN THE POINTS WHERE SEVERAL CIRCUITS BRANCH AND WHERE THEY AGAIN UNITE, *is equal to the sum of the currents in all the branches, multiplied by the joint resistance of the branches.*

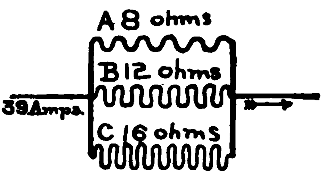


Fig. 120.—Finding the Current Strength through the Branches of a Divided Circuit.

E = potential difference across branches; I, I_1, I_2, etc. = current in the branches; J. R. = joint resistance of the branches, Fig. 119.

$$E = (I + I_1 + I_2, \text{ etc.}) \times J. R. \quad . \quad . \quad . \quad . \quad . \quad (47).$$

Prob. 62: Three coils, A, B, and C, have a resistance of 8, 12, and 16 ohms respectively. Find the potential difference required to send 18 amperes through A, 12 amperes through B, and 9 amperes through C.

From Prob. (61) Joint conductance $= \frac{13}{48}$ mho, therefore

$$\text{Joint resistance} = \frac{48}{13} = 3.69 \text{ ohms.}$$

By Formula (47) $E = (I + I_1 + I_2) \times J. R. = (18 + 12 + 9) \times 3.69 = 143.9$ volts.

$I = 18$ amperes, $I_1 = 12$ amperes, $I_2 = 9$ amperes, J. R. $= 3.69$ ohms.

161. Current in Branches of Multiple Circuits.—THE CURRENT, IN ANY BRANCH OF A MULTIPLE CIRCUIT, IS FOUND, *by dividing the potential difference between where the branches divide and unite, by the separate resistance of each branch.*

The separate resistances of the branches of a multiple circuit may be found by dividing the potential difference across any branch by the current flowing through any branch, according to Ohm's Law.

Prob. 62-A: Find the current through each branch of the divided circuit in Fig. 119, if the potential difference is 24 volts.

By ¶ 161 $I = \frac{E}{R} = \frac{24}{2} = 12$ amperes.

Also $\frac{24}{4} = 6$ amperes and $\frac{24}{8} = 3$ amperes.

162. Shunts.—If the current passing through the galvanometer G, Fig. 121, is too large, or the wire with which it is wound too small to carry a large current, only a small frac-

tion of the total current may be passed through the galvanometer, the remainder passing through the wire, S, connected across the galvanometer terminals. The wire, S, forms a "by-path" for the current, and is called a *shunt*, and the galvanometer is said to be *shunted*. If the resistance of the galvanometer is 1 ohm and the shunt 1 ohm, then as much current will flow through the shunt as through the galvanometer. If the resistance of the galvanometer is 2 ohms and the shunt 1 ohm, then twice as much current will flow through the shunt as through the galvanometer; that is, the galvanometer reading must be multiplied by 3 to obtain the total current flowing from the battery. The value 3 is called the *multiplying power of the shunt*, that is, it is the amount by which the shunt multiplies the range of the galvanometer. Any galvanometer (ammeter or voltmeter) may, therefore, have its range of indication increased by shunting it.

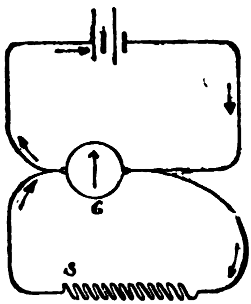


Fig. 121.—A Shunted Galvanometer.

Let G = galvanometer resistance;
S = shunt resistance;
I = total current in the joint circuit;
Ig = current in the galvanometer circuit.

The multiplying power of a shunt is the ratio of the total current flowing in the circuit, I, to that part of it, Ig, which flows through the galvanometer. The total current, I, bears the same ratio to the galvanometer current, Ig, that the sum of the resistances, G + S, bears to the shunt resistance.

$$\text{Thus: } \frac{I}{Ig} = \frac{G+S}{S},$$

$$\text{or } \frac{G+S}{S} = \frac{G}{S} + \frac{S}{S} = \frac{G}{S} + 1.$$

1. To Find the Multiplying Power of a Shunted Galvanometer:

Divide the galvanometer resistance by the resistance of the shunt and add one to the quotient.

$$\text{Multiplying power of a shunt (n)} = \frac{G}{S} + 1 \quad . \quad . \quad . \quad \textbf{(48)}.$$

Prob. 63: Find the number by which the readings on a Weston voltmeter must be multiplied (or the multiplying power of the shunted galvanometer) in Fig. 122, when resistance of voltmeter (galvanometer) is 5000 ohms, and resistance of shunt placed across its terminals is 500 ohms.

By Formula (48) $n = \frac{G}{S} + 1 = \frac{5000}{500} = 10 + 1 = 11.$

The readings are to be multiplied by 11 to obtain the true value of the total current flowing.

2. To Find the Current Flowing Through a Shunted Galvanometer, Ig, When the Total Current, I, Flowing Through the Circuit is Known:

Divide the total current by the ratio of the galvanometer resistance to the shunt resistance, plus one.

$$Ig = \frac{I}{\frac{G}{S} + 1} \quad . \; . \; . \; . \; . \; (49).$$

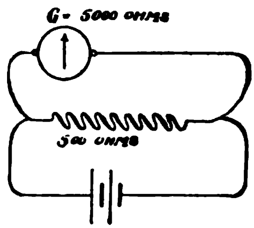


Fig. 122.—Current Through a Shunted Galvanometer.

Prob. 64: If 30 amperes flow from the battery in Fig. 122, when the galvanometer resistance is 5000 ohms and the shunt 500 ohms, what current will flow through the galvanometer?

By Formula (49) $Ig = \frac{I}{\frac{G}{S} + 1} = \frac{30}{\frac{5000}{500} + 1} = \frac{30}{11} = 2.7$ amperes.

3. To Find the Value of a Shunt's Resistance to Give a Certain Multiplying Power (n):

Divide the galvanometer resistance by the multiplying power desired, minus one.

Let n = the desired multiplying power;
S = shunt's resistance;
G = galvanometer resistance.

$$\text{Then,} \qquad S = \frac{G}{n - 1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (50).$$

Prob. 65: What must be the resistance of a shunt to give a multiplying power of 100, when used with a galvanometer of 5000 ohms resistance? Fig. 122.

By Formula (50) $S = \frac{G}{n - 1} = \frac{5000}{100 - 1} = \frac{5000}{99} = 50.5$ ohms.

In practice n, is generally 10, 100, or 1000.

These three shunt coils, calculated for any particular galvanometer, are arranged in a plug box, called a shunt box, similar to Fig. 125, and by withdrawing the plugs any particular shunt can be quickly connected to the galvanometer. The multiplying power is stamped on the box to correspond with each plug. This shunt box can only be used with the galvanometer (ammeter or voltmeter), for which it was calculated. Shunt boxes are sometimes called *multipliers.* By connecting a shunt across a galvanometer the resistance of the circuit is decreased. If it is desired to keep the resistance the same as when the galvanometer was not shunted, another resistance, known as a *compensating resistance*, is added in series with the shunted galvanometer. The value of the resistance to be added equals $G \times \frac{n-1}{n}$.

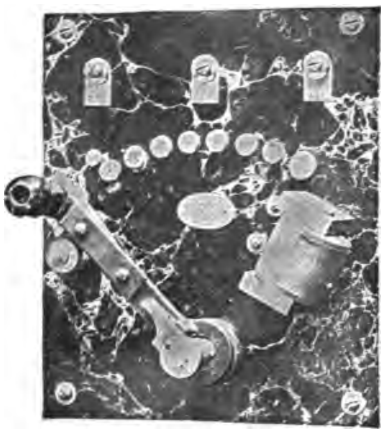


Fig. 123.—Commercial Type of Rheostat.

163. Rheostats.—The usual method of regulating and controlling the current required for various electrical purposes is by inserting, or taking out of a circuit, resistance. It will be seen, from Ohm's Law, $I = \frac{E}{R}$, that if the pressure (E) is constant the current (I) can readily be regulated by increasing or decreasing the value of R; that is, changing the resistance in circuit. An adjustable resistance or any apparatus for changing the resistance without opening the circuit is called a *rheostat.* The function of a rheostat is to absorb electrical energy, and this energy, which appears as heat, is wasted instead of performing any useful work. A rheostat may be constructed of coils of iron wire, iron plates or strips; carbon, either pulverized in tubes or in the form of solid rods or discs; German silver, platinoid, etc., wound on spools; columns of liquids, as water and mercury, etc. The cross-sectional area of the material must be sufficient to carry the current without excessive heating. In rheostats used for

regulating the current in commercial electric circuits no great degree of accuracy of the resistance coils is required, as is the case in laboratory rheostats, ¶ 165. Fig. 123 illustrates a *commercial type of rheostat,* in which the various coils are connected to brass buttons or contact segments. By moving a metallic connecting arm over the segments the coils are thrown in or out of circuit, and the resistance thus readily adjusted, as shown in the diagram of connections, Fig. 124. In some types of rheostats the wire is wound around an iron framework which has been previously dipped into a fireproof insulating enamel. The advantage of this construction is that the heat from the wire is dissipated much more rapidly, so that a much smaller wire can be used to carry a given current. The size of such an enameled rheostat, required for absorbing a given amount of energy, is much smaller than one made of coils of wire stretched between an iron supporting frame-work.

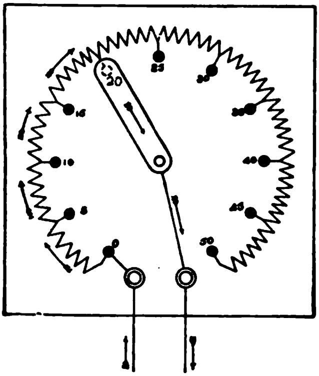


Fig. 124.—Commercial Rheostat.

Diagram of connections of the resistance coils.

164. Resistance of Connections.—When two surfaces are pressed *lightly* together the resistance of the contact is much greater than if the surfaces of contact are *firmly* pressed together. For this reason all joints in electrical conductors should be soldered to decrease the resistance of contact; all binding screw contacts and connections should be thoroughly cleaned and of a bright

Fig. 125.—Laboratory Type of Rheostat.

metallic color when used, and screwed down so as to clasp the wires firmly.

165. Laboratory Rheostats.—For making electrical measurements accurately standardized resistance boxes are required. The current passed through these rheostats is generally a fraction of an ampere, so that the resistance wire, mostly German silver or platinoid, is small in size and is wound on spools which are contained in a case, as shown in Fig. 125. Brass strips are mounted on the top of the case, and the terminals of each coil connected to two adjacent strips as shown in detail in Fig. 126. The insertion of a tapered metal plug into a tapered hole formed by the adjacent strips, short circuits or cuts out the resistance coil. By removing the plugs, resistance is inserted in the circuit in which the box is connected. The accurate resistance of each coil is stamped on the box, as shown in Fig. 234, so that the resistance in circuit is found by the addition of the values of the coils unplugged. The coils are wound *non-inductively*, ¶ 299, and the size of the wire used must be such that no appreciable error will be introduced by the heating of the coils.

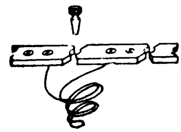


Fig. 126.—Connection of a Resistance Coil.

Table X.—Resistances of Commercial Apparatus.

GALVANOMETERS.	
Thomson mirror galvanometer, ...	1 ohm to 350,000 ohms.
" " " common resistance, . . .	5,000 "
D'Arsonval galvanometer, ...	1 ohm to 750 "
" " common resistance,	250 "
AMMETERS.	
Resistance is less the larger the size of instrument required.	
Weston, 15 amperes capacity, ...	.0022 ohm.
VOLTMETERS.	
Cardew voltmeters for 100 volts, about, ...	500 ohms.
Weston " " 150 " "	150000 "
BATTERIES.	
Gravity cell, ...	2 to 4 ohms.
Leclanche, ...	1 "
Bichromate, ...	.4 "
Edison-Lalande, 300 ampere-hours, ...	.02 "
Accumulator, 100 ampere-hours, ...	.005 "

TELEGRAPHY.

Sounders,	20 ohms
Neutral relays,	80 to 300 "

TELEPHONY.

Bell telephone, about,	75 ohms.
Call bell, from,	75 to 1000 "
Magneto armature,	500 "
Induction coil, primary,	0.28 "
" " secondary,	12 to 160 "

DYNAMOS AND MOTORS.

Armature resistance (warm) .5 K. W. dynamo or motor, about,	4.	ohm.
And between brushes, 3 K.W. dynamo or motor, about,	0.4	"
And between brushes, 20 K. W. dynamo or motor, about,	0.025	"
And between brushes, 100 K. W. dynamo or motor, about,	.0055	"
And between brushes, 200 K. W. dynamo or motor, about,	.0024	"

ALTERNATING CURRENT TRANSFORMERS.

0.5	K. W.	capacity,	primary,	21.8 ohms,	secondary,	.04	ohm.
2.	"	"	"	5.5 "	"	.015	"
20.	"	"	"	0.48 "	"	.0015	"

INCANDESCENT LAMPS—CARBON FILAMENTS

At	52	volts,	a 16	candle-power	lamp	(hot),		48	ohms.
"	"	"	" 24	"	"	"	"	32	"
"	110	"	" 10	"	"	"	"	343	"
"	"	"	" 16	"	"	"	"	215	"
"	"	"	" 24	"	"	"	"	144	"
"	"	"	" 32	"	"	"	"	107	"
"	"	"	" 50	"	"	"	"	69	"

HUMAN BODY.

The resistance of the human body varies widely with the position of electrodes, their area, the dryness of the skin, the duration of application, and the current strength. A very low resistance recorded, was 214 ohms from surface of head to surface of right calf, and 500 ohms from hand to hand, each immersed to the wrist in salt water. Average resistance under latter conditions, 1000 ohms.

QUESTIONS.

1. The arc lamps connected to a series dynamo are joined in series with it. How is the resistance of the circuit affected as additional lamps are inserted in the circuit?

2. What is a shunt? What advantages does it possess when used with a galvanometer?

3. A number of incandescent lamps are connected in multiple and to a dynamo. How will the resistance of the circuit be affected if one lamp is turned off?

4. What advantage does an enamel type of rheostat possess over one constructed in the ordinary manner?

5. State for what uses laboratory and commercial types of rheostats are designed, and also the essential differences between them.

6. An electric heater consists of coils of iron wire through which a current of 2.5 amperes flows, when joined in parallel with an incandescent lamp which receives one ampere. Which object possesses the higher resistance? Give proof for answer.

7. If a joint in an electrical current is mechanically stronger than the wire of which it is made, why should it be necessary to solder it?

8. Two resistances, A and B, having 3 mhos and 1.5 ohms respectively, are connected in parallel and to a source of current. Which one will receive the greater current?

PROBLEMS.

1. Four hundred incandescent lamps are connected in parallel to a dynamo circuit. Resistance of the line .5 ohm and hot resistance of 1 lamp 220 ohms. Potential difference at dynamo terminals 112 volts. What current flows through the circuit? Give sketch. *Ans.* 106.66 amperes.

2. What length of No. 24 B. & S. copper wire would have an equivalent resistance to the joint resistance of 2 lamps connected in parallel? One lamp has a resistance of 110 ohms, the other 33 ohms. Give sketch. *Ans.* 950.27 feet.

3. Three copper electroplating baths are connected in parallel and to a dynamo which furnishes 117 amperes to them. The resistance of the baths is, No. 1, 24 ohms; No. 2, 36 ohms; No. 3, 48 ohms. What current does each bath receive? Give sketch. *Ans.* 54; 36; 27 amperes.

4. What potential difference must be maintained across the multiple circuit in Prob. 3? *Ans.* 1296 volts.

5. Sketch and name six combinations of 4 incandescent lamps connected to a pair of supply lines. Each lamp has a resistance of 220 ohms (hot) and the potential across the mains is 110 volts. What current will each combination receive? *Ans.* .125; 2, .5; .2; .376; .3 amperes.

6. In a trolley car, 5 lamps, each requiring ½ ampere and 100 volts, are connected in series and between the line and track across which 500 volts potential is maintained. If 10 cars wired as above were running, what would be the joint resistance of the lamp circuit and how much current would flow from the power station? *Ans.* 100 ohms J. R.; 5 amperes.

7. The resistance of an ammeter shunt is 0.2 ohm and the instrument with its leads 24 ohms. What pressure is required to send 10 amperes through the joint resistance of the ammeter and its shunt in parallel? *Ans.* 1.9 volts.

8. How much of the current flows through the ammeter in question 7? *Ans.* .082 ampere.

9. What is the multiplying power of the above shunt? *Ans.* 121.

10. Two electromagnets of 8 and 20 ohms respectively are joined in parallel. If 10 amperes flow through the 8-ohm magnet, what current does the 20-ohm magnet receive? *Ans.* 4 amperes.

LESSON XV.

ELECTROMAGNETISM.

Electromagnetism—Direction of the Lines of Force of a Straight Current-Carrying Wire—Deflection of a Horizontal Magnetic Needle—Right-Hand Rule for Direction of Whirls—Right-Hand Rule for Direction of Current or Deflection of Needle—Magnetic Field of a Circular Wire Carrying a Current—Magnetic Field at the Centre of a Circular Current—Magnetic Polarity of a Circular Current—The Helix and Solenoid—Testing the Polarity of a Solenoid—Rules for Determining the Polarity of a Solenoid—Graphical Field of a Solenoid—Questions.

166. Electromagnetism.—

Exp. 47: Connect three or four chromic acid cells in parallel, close the circuit through a heavy bare copper wire, and then plunge the wire into iron filings. The filings are attracted to all sides of the wire, as though it were a magnet. Any part of the wire will attract

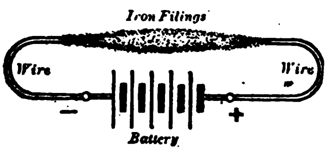
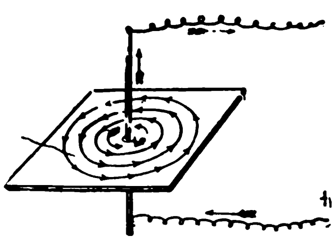


Fig. 127.—A Current-Carrying Wire Attracting Iron Filings.

the filings when the current is flowing, and the attraction will be equal on all sides of the wire, Fig. 127. When the circuit is broken the filings drop off of the wire.



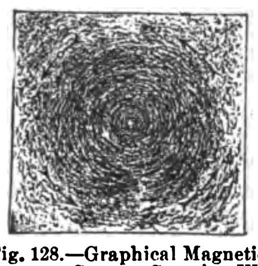


Fig. 128.—Graphical Magnetic Field of a Current-Carrying Wire.
Made by iron filings.

Electromagnetism, as distinguished from magnetism in a permanent steel magnet, *is the magnetism produced around a conductor when a current flows through it.* A current of electricity is defined, in part, as the

magnetic field set up around a current-carrying conductor. Every wire carrying a current possesses this magnetic field, which fact can be proved by bringing a compass needle near the wire. The magnetic field of the wire acts on the magnetic field of the compass needle, and it is deflected.

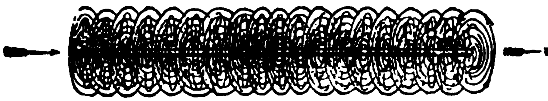


Fig. 129.—Magnetic Whirls of a Current-Carrying Wire.

Exp. 48: Pass a heavy copper wire vertically through the centre of a piece of cardboard held horizontally, upper view of Fig. 128, and send a strong current through the wire. Tap the card while sifting filings upon it, and they arrange themselves in concentric circles around the wire and at right angles to it. The plan view of Fig. 128 illustrates a graphical field made in this manner. By using paraffin paper the field may be fixed by applying heat.

The filings are magnetic bodies free to move, and arrange themselves in the circular direction of the magnetic lines of force surrounding the wire. A compass needle held near the wire will take up a position tangent to the circular field at any point, whether the current be passed up or down the wire. The magnetic field, around a straight wire carrying a current, consists of a cylindrical whirl of circular lines, their density decreasing as the distance from the wire increases, as illustrated in Fig. 129. The circular lines of force, or *magnetic whirls*, do not merge into, cross, or cut each other, but complete their circuits independently around the wire.

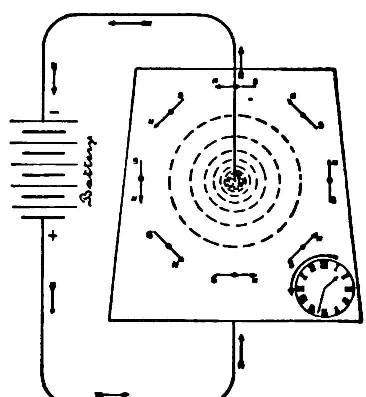


Fig. 130.—Current Flowing Up—Whirls Anti-Clockwise.

The compass needles on the horizontal cardboard arrange themselves in the direction of the current's field.

167. Direction of the Lines of Force of a Straight Current-Carrying Wire.—

Exp. 49: Pass a wire vertically through a sheet of cardboard held horizontally. Arrange a number of poised needles or compasses

around the wire in the form of a circle, Fig. 130, of such diameter that all the needles point nearly N and S. Pass a strong current through the wire from a battery so that the current flows up, or toward you as you look down upon the cardboard.

When the current flows up through the wire, Fig. 130, the needles, being magnetic bodies, arrange themselves around it in the direction of the circular lines of force, also so that the needles' magnetic lines of force are in the same direction as the magnetic lines of the circular field, ¶ 43. The N-poles of the needles point in the same direction as the magnetic lines of the current, and these lines pass through each of the needles, entering at the S-pole and emanating at the N-pole. The direction of the field with the current flowing up is left-handed, or opposite to the direction in which the hands of a watch

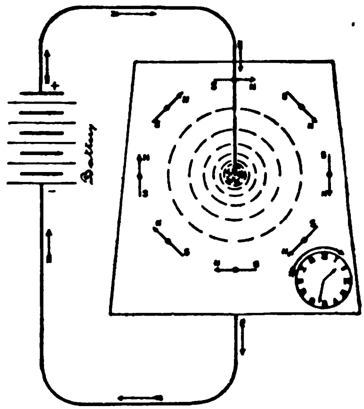


Fig. 131.—Current Flowing Down—Whirls Clockwise.

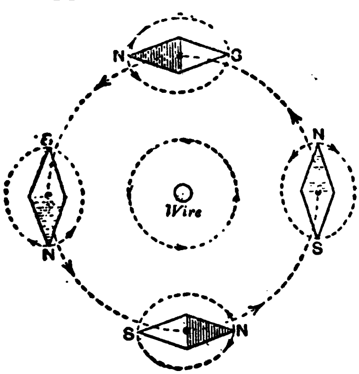


Fig. 132.—Direction of Whirls when the Current Flows Toward You—Anti-Clockwise.

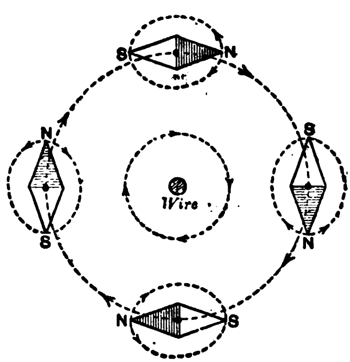


Fig. 133.—Direction of Whirls when the Current Flows Away from You—Clockwise.

would move, as shown in Fig. 130 and also 136, where the wire is supposed to be passed through the watch with the

current flowing toward you as you look at its face. Reverse the direction of the current so that it now *flows down* through the cardboard, or along the wire in the same direction that you are looking. The needles now reverse their direction, and the **N**-poles point around the wire in the opposite direction to what they did in the previous case, Figs. 131 and 133. The direction of the lines of the circular field is therefore reversed, or is in the same direction as the hands of a watch move, Figs. 131 and 136.

The direction of a current's circular magnetic field is the same as the natural direction of the magnetic lines through a poised or suspended needle when brought under the influence of the current's field. The direction the needles take up around the wire, right-handed or left-handed, is another reason for assuming that a current has direction. The direction of current in any vertical wire can thus be determined by a single magnetic needle, by noting the general direction its **N**-pole points when presented near to the wire.

If the **N**-*pole points clockwise as you look down upon it the current is flowing from you, or in the same direction as that in which you are looking; if anti-clockwise, the current is flowing toward you.* Compare Figs. 132 and 133 with Fig. 136.

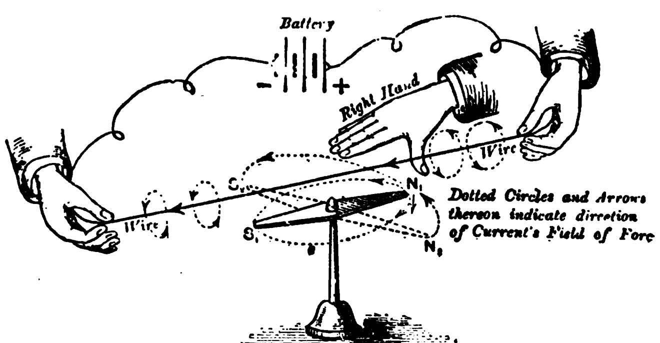


Fig. 134.—A Magnetic Body Free to Move, etc., ¶ 43.

Exp. 50: Figs. 132 and 133 show a plan view of the position of the needles on a horizontal piece of cardboard, with a vertical wire passed through it, when the current flows in opposite directions. Using a single compass needle, the student should verify the diagrams and make notebook sketches.

168. Deflection of a Horizontal Magnetic Needle.— When a wire is held horizontally over a poised magnetic needle, pointing **N** and **S** (or in the magnetic meridian), Fig. 134, and a current passed through it, the needle is deflected and tends to take up a position at right angles to the wire. When the current is sufficiently strong, the needle moves, so that it will accommodate through itself the greatest number of magnetic lines of the circular field, and also to such a position that its own natural magnetic lines will be in the same direction as the current's lines of force.

Considering Fig. 134, the current flows over the needle from right to left (also **N** to **S**). As you look along the wire in the direction of the current the direction of the whirls is right-handed or clockwise, as indicated by the dotted circles in Fig. 134, and also on the lower diagram of Fig. 136, the **N**-pole

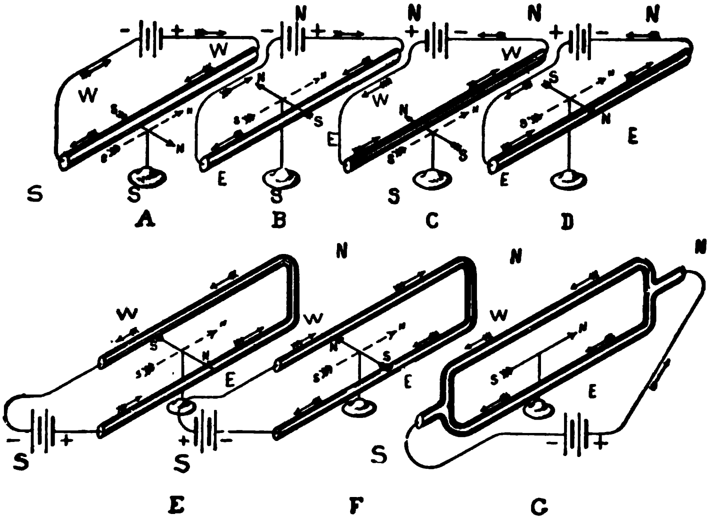


Fig. 135.—Resultant Deflections of the Magnetic Needle When Placed Near to a Current-Carrying Wire.

of the needle, N_1, moves to the position, N_2, at right angles to the wire, and in the direction of the field underneath the wire (which is from S_2 to N_2), so that the direction of the whirls and the needle's natural lines are coincident.

Consider the right hand, Fig. 134, as **N**, and the left hand

as S. The direction of the current's field underneath the wire is then from west to east, and the N-pole of the needle is deflected east. *When a current flows from* **N***orth* **O***ver a needle to* **S***outh the N-end is deflected* **E***ast.* See A of Fig. 135. This may be remembered by the combination of the above letters, which forms the word **NOSE**. The converse of this statement is also true. If a needle held under a wire pointing **N** and **S** is deflected east when the current is flowing, the direction of the current is from **N** to **S.** Obviously, when the needle is held above the wire in Fig. 134, the **N**-pole will point west, since the direction of the circular field above the wire is opposite to its direction underneath the wire (B, Fig. 135). Now consider the battery terminals reversed in Fig. 134, so that the current flows from **S** to **N** (left to right); the direction of the circular field is reversed and the **N**-pole of the needle points west.

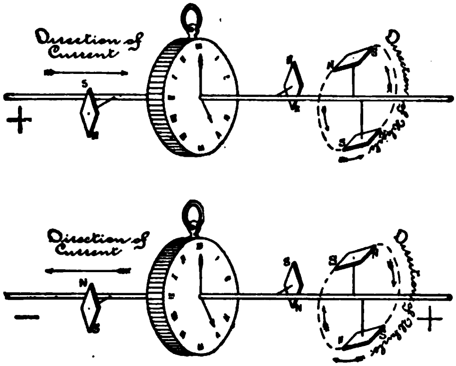


Fig. 136.—Clock Rule for the Direction of Whirls Around a Straight Wire.

When a current flows from **S**outh to **N**orth **O**ver a needle, the N-end is deflected **W**est. (C of Fig. 135.) This combination forms the word **SNOW**. The converse is also true: if the **N**-pole of a needle held under a wire pointing **N** and **S** is deflected west, the direction of the current is from **S** to **N**. With the current from **S** to **N**, when the needle is held above the wire, the **N**-pole is deflected east (D of Fig. 135). When a current flows from **N** to **S** over a wire in the magnetic meridian and from **S** to **N** under it, the **N**-end of the needle is deflected east to an increased extent. (Compare A and D with E of Fig. 135.) This forms a single turn, or convolution, and increasing the number of convolutions increases the extent of the needle's deflection till it assumes a position at right angles to the wire when the current is sufficiently strong. With the

current reversed in the above condition, the **N**-end of the needle is deflected west. (Compare B and C with F, Fig. 135.) The current flowing in *opposite directions*, above and below the needle, *increases* the amount of deflection. Equal currents flowing above and below the needle, in the *same direction*, produce *no deflection*. (G, Fig. 135.) If two unequal currents flow, one above and the other below the needle, the needle obeys the directive force of the stronger current.

Exp. 51: A simple form of apparatus for studying the relation between a needle's deflection and the direction of current, called an Oersted stand, is shown in Fig. 137. It consists of two parallel brass rods provided with binding posts and supported from a wooden base. With it the student should verify all the cases given in Fig. 135 and make notebook sketches.

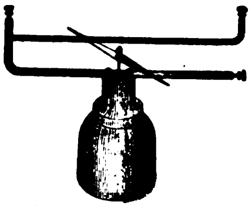


Fig. 137.—Oersted Stand for Studying the Needle's Deflections by a Current.

169. Right-Hand Rule for Direction of Whirls.—IF THE DIRECTION OF CURRENT IN ANY CIRCUIT IS KNOWN, THE DIRECTION OF THE CIRCULAR MAGNETIC FIELD AROUND THE WIRE MAY BE FOUND AS FOLLOWS:

Place the palm of the outstretched RIGHT *hand above the wire, with the fingers pointing in the direction of the current, and the outstretched thumb extended at right angles and* UNDERNEATH *the* WIRE. (See right hand, Fig. 134.) *The direction in which the thumb points will indicate the direction of the circular field around the wire.*

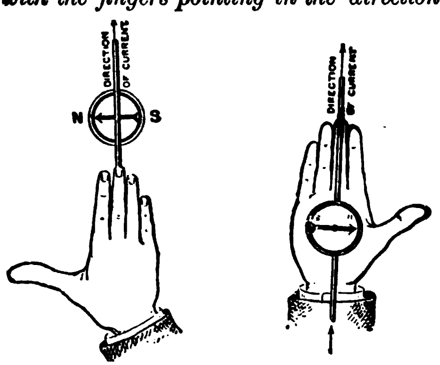


Fig. 138.—Right-Hand Rule for Finding Direction of Current or Needle's Deflection.

170. Right-Hand Rule for Direction of Current or Deflection of Needle.

TO FIND THE DIRECTION THE N-POLE OF A NEEDLE WILL BE DEFLECTED BY A CURRENT:

Arrange the wire above and parallel to the needle when it is at

est, and place the palm of the outstretched RIGHT *hand on the wire with the fingers pointing in the direction of the current,* Fig. 138, *the outstretched thumb at right angles to the hand will point in the direction that the* **N**-*pole of the needle will turn.*

To Find the Direction of the Current when the Direction of Deflection of the **N**-Pole of the Needle is Known:

Arrange the wire **N** *and* **S** *over the needle, and place the palm of the* RIGHT *hand over the wire, with the outstretched thumb at right angles to the wire and pointing in the direction that the* **N**-*pole turns. The fingers point in the direction that the current flows.* This rule also holds good if the compass is above the wire and the right hand below it, Fig. 138.

171. Magnetic Field of a Circular Wire Carrying a Current.—

Exp. 52: Arrange a circular turn of wire vertically and in the magnetic meridian so that one-half of the circle will be above a horizontal piece of cardboard, as in Fig. 139. Pass a current through the wire, and while tapping the cardboard sift iron filings over it.

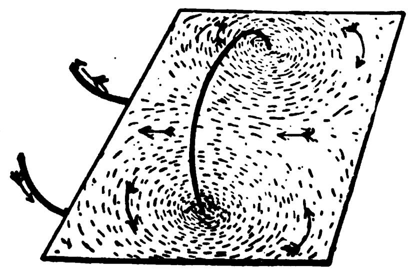


Fig. 139.—Graphical Field of a Circular Current.
Made with the aid of iron filings.

The iron filings arrange themselves circularly around the wire. Near the centre of the loop the filings are nearly parallel with its axis. Explore the field inside and out with a compass needle; the needle at any point lies in the direction of the filings at this point, and its **N**-pole points in the direction of the current's field. The arrows in Fig. 139 indicate the direction of the whirls, and the several positions of the needle.

Apply the right-hand test, ¶ 170, and it will confirm the position the needles take up at any point. On one side of the loop all the whirls enter it in the same direction, and emerge from the opposite side as is further shown in Fig. 140.

172. Magnetic Field at the Centre of a Circular Current.—If a magnetic body, A, Fig. 140, be held above the circular loop, through which a current is flowing, it will tend to move downward through the loop, with its axis coinciding with the axis of the loop, until its position accommodates

through itself the greatest number of lines of force of the current's field, ¶ 43. There will be the same tendency in B, Fig. 141, where the current is flowing in a rectangular circuit; but it will be seen from inspection of the two figures that many more of the current's lines act upon the magnetic body, A, when the circuit is in the form of a circular loop than when in a rectangular or any other form, Fig. 141. If the distance between the two parallel wires in the rectangular circuit is equal to the diameter of the circular loop, Fig. 140, it can be mathematically and experimentally proved that the strength of the magnetic field, at the centre of the circular current, is 1.57 greater than the strength of field midway between the two straight currents. For this reason nearly all magnet windings, bobbins of galvanometers, etc., are made circular to obtain the maximum magnetic effect of the current.

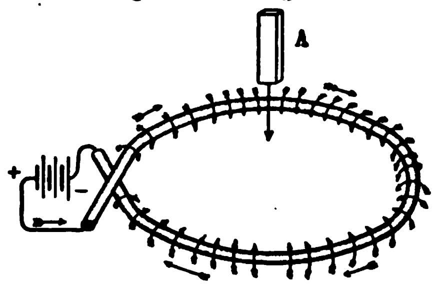


Fig. 140.—Attraction of Magnetic Body (A) by the Magnetic Field of the Circular Current

173. Magnetic Polarity of a Circular Current.—Under the subject of magnetism, we assumed the magnetic lines of force to pass out from the N-pole of a bar magnet and enter the magnet again at its S-pole; a similar reasoning is applied to the magnetic lines of force of an electric circuit. In the single turn of the copper ribbon, A, Fig. 142, the current flows around the loop in the direction of the hands of a watch as viewed from the nearer end. The circular whirls are also clockwise, if you look along the ribbon in the direction of the current. The magnetic whirls, therefore, all enter the loop through its nearer side, or face; consequently, this face possesses S-polarity, and as the same

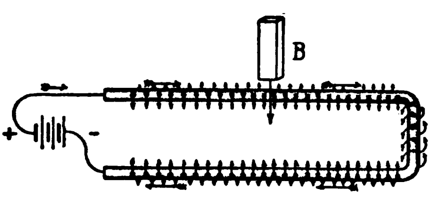


Fig. 141.—Attraction of Magnetic Body (B) by the Current's Field.

lines emanate again from the more distant face, that face is of **N**-polarity. The single turn of wire, therefore, possesses polarity similar to a bar magnet, and when free to move will take up a position in the earth's field with its **N**-face pointing toward the **N**; also, its **N**-face will be repelled by the **N**-pole of a bar magnet, or similar loop, and attracted by the magnet's **S**-pole, according to the law of attraction and repulsion between magnets. When the current is sent the opposite way around the single turn, B, Fig. 142, the direction of the whirls is reversed and the lines now emanate from the nearer or **N**-face of the loop, and enter by the more distant **S**-face. The polarity of the loop is, therefore, reversed as compared with the previous case. The above principles may be demonstrated by Exp. 53

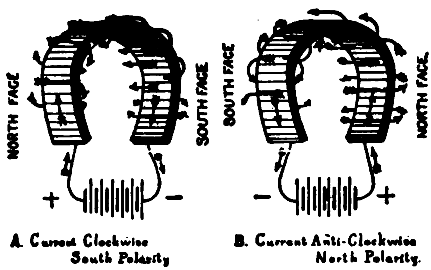


Fig. 142.—Polarity of a Single Turn of Wire.

Exp. 53: Fasten a piece of copper and zinc to a large cork. Connect the plates by a circular turn of heavy wire, Fig. 143, and immerse them in a jar containing dilute sulphuric acid. Present a bar magnet's **S**-pole to the **N**-face of the turn in the direction of its axis; the coil will be attracted, and carrying the cell with it, move along the magnet till it reaches the middle point, or equator. The figure also illustrates the direction of the current's and magnet's magnetic lines. The laws of attraction and repulsion should be verified and sketches made.

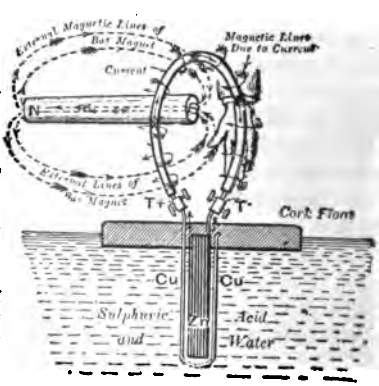


Fig. 143.—Testing the Polarity of a Single Turn of Wire.

The turn is connected to a floating battery and is free to move.

174. The Helix and Solenoid.—A coil of wire wound so as to follow the outlines of a screw without overlaying itself is termed a *helix*, Fig. 144, and may be wound right or left-

handed. The polarity can be reversed by re-winding in the opposite direction and passing the current, as indicated in Fig. 144, or by simply sending the current through the helix in the opposite direction. A *solenoid* is a coil of wire, generally wound on a wooden or brass spool, the length of which is much greater than the diameter, Fig 145. The winding is always in the same direction, layer upon layer, similar to the winding of a spool of thread. The spirals of a helix or solenoid are equivalent in their magnetic action to as many circular currents as there are convolutions of wire, since their axes lie in the same straight line. The magnetic whirls of each turn inside the helix are in the same direction as every other turn, and the direction of the magnetic field along, and parallel to the axis of the solenoid, is straight and fairly uniform to within a short distance of the ends. The total field is the sum of the magnetic lines of each individual turn as illustrated in the helix, Fig. 146, where the whirls of one convolution are depicted as joining on to the next, the sum of all

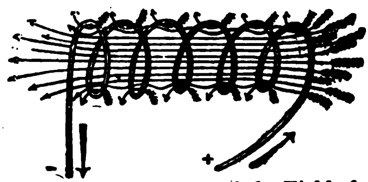


Fig. 144.—Direction of the Field of a Helix.

Fig. 145. Solenoid.

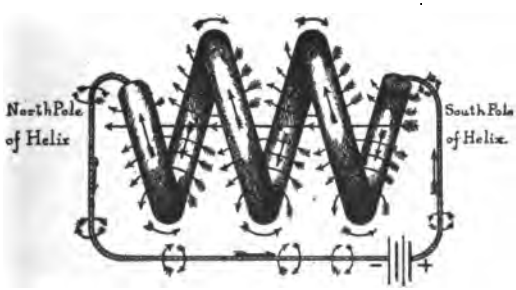


Fig. 146.—Polarity of the Helix.

The whirls of one turn unite with those of the next.

the turns constituting the field, or total number of lines of force passing through the helix. This diagram shows the direction of current through the helix, the direction of the

whirls around each convolution, and the resulting polarity. The action is similar for another set of convolutions wound over this set in the same direction, or for a solenoid composed of any number of layers of winding, the field increasing with the number of turns and layers so wound.

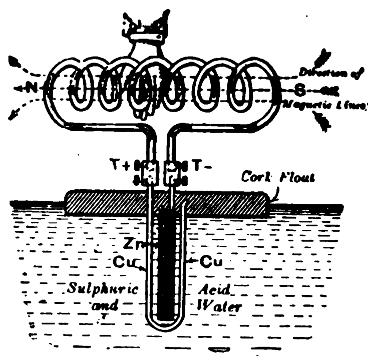


Fig. 147.—Testing the Polarity of a Helix.

The helix is connected to a floating cell.

175. Testing the Polarity of a Solenoid.—When a current is passed through a solenoid it is termed an electromagnetic solenoid, and in its action it behaves similar to a magnet. It may be tested by the floating cell arrangement, Fig. 147, which is similar to that described in Exp. 53, or by the poised solenoid, Fig. 148, in which the two terminals of the movable solenoid dip into two concentric circular grooves containing mercury in which contact is made. One groove is connected to each binding post by a wire, the groove stamped A, corresponding with post A, so that the direction of the current may be traced. When a current is sent through the coil it takes up a position **N** and **S** just as in the case of the poised needle, and is also repelled or attracted by another magnet or solenoid, the polarity being as explained for a single convolution, ¶ 172.

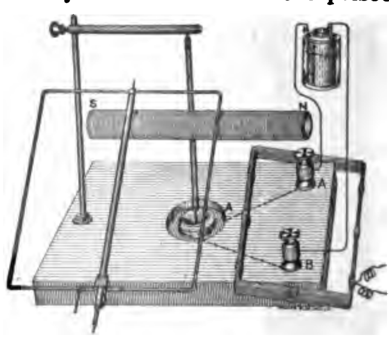


Fig. 148.—Ampere Frame Stand with Coils.

The movable coils are poised on needle points and the terminals dip in concentric mercury cups.

176. Rules for Determining Polarity of a Solenoid.—Clasp the solenoid, or helix, in the *right hand* so that the fingers point around it in the direction that the current flows. The outstretched thumb, at right angles with the fingers, will point in the direction of the **N**-pole of the solenoid, Fig. 149.

To find the direction of current around the coil when the polarity is known: clasp the coil with the right hand, so that

the thumb outstretched at right angles will point toward the N-pole, then the fingers will point in the direction of the current.

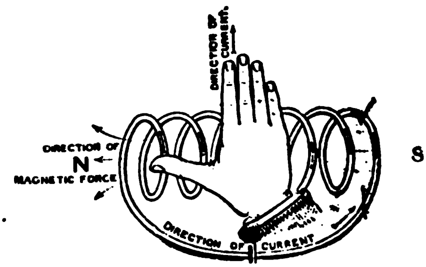


Fig. 149.—Right-Hand Rule for the Polarity of a Solenoid.

If on viewing the end of a solenoid the current flows around that end, in the same direction that the hands of a watch move, Fig 150, that end is **S**-polarity. If the current flows around the coil against the direction in which the hands of a watch move, that end possesses **N**-polarity.

177. Graphical Field of a Solenoid.—The distribution of magnetism around a solenoid is very similar to that of a bar magnet, and can be studied by the iron filing diagram, Fig. 151.

Exp. 54: Cut a piece of cardboard to fit around a solenoid, as in Fig. 151. Place the cardboard horizontally so that its plane is in the axis of the coil. Pass a current through the coil, and while gently tapping the cardboard sift iron filings on it to produce a graphical field.

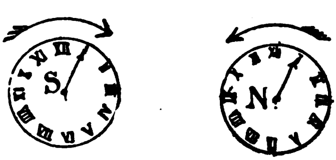


Fig. 150.—Clock Rules for Polarity.

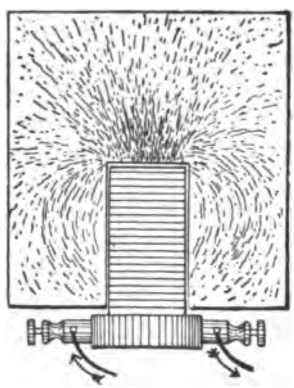


Fig. 151.—Magnetic Field of a Solenoid.

Made by iron filings upon a horizontal piece of cardboard.

Exp. 55: Wind a helix about 1 inch in diameter and 4 inches long. Cut a tongue in a sheet of cardboard equal to the inside diameter of the helix, and pass it horizontally through the helix with its plane in the axis of the helix. Make a graphical internal field of the helix. The direction of the lines of force may also be explored by a compass needle.

QUESTIONS.

1. A feed wire for the overhead trolley line is conducted up a vertical wooden pole from an underground duct. When you approach the pole from the S the N-end of a compass needle held in your hand is deflected east. Is the current flowing up or down the pole?

2. One end of an arc lamp solenoid attracts the N-pole of a compass needle. What is the direction of the current around the coil when viewed from this end?

3. There is a leak to ground on a telegraph line between two stations 50 miles apart, so that the current transmitted does not reach the receiving apparatus. State how, by the use of a compass needle, you would proceed to accurately locate the point at which the leak exists? Make sketch.

4. Two parallel lines, one above the other, are stretched in a N and S-direction, and an equal current flows through each in the same direction. A compass is held midway between the wires. How will its needle be affected? Make sketch.

5. Six successive turns are made in a right-hand direction around a lead pencil, and the following six successive turns are wound in the opposite direction. A current is passed through the wire. Sketch the direction of the magnetic field you would expect to see if iron filings were used, and indicate the polarity and direction of the current.

6. A current is sent through a coil of wire wrapped around a tumbler in the same direction that the fingers of the right hand point when clasping it to drink. What is the polarity of that end of the coil you observe while drinking?

7. A current is passed through a wire held east and west over a compass needle. How will the needle be affected? Make sketch.

8. You are given the terminals of a cable containing the positive and negative poles of 5 batteries. The terminals are to be connected so that the cells will all be in series. How would you proceed by the use of a galvanometer to determine the polarity and make the connections? Give sketch.

9. The N-pole of a bar magnet, lying on a table with its axis pointing east and west deflects the N-pole of a compass needle 20 degrees. A wire carrying a current is held over the compass in a N and S-direction and the deflection is now only 12 degrees. How do you account for this?

10. What is the direction of current through the wire in question 9? Make sketch.

11. An electric light wire is run up the S-wall of a building from the first to the second story. Walking toward the wire the N-pole of a compass held in your hand is deflected east. What is the direction of the current in the wire? Make sketch.

12. There is a break in a 5-pound spool of magnet wire. How would you proceed to locate it by the use of a battery and galvanometer?

LESSON XVI.

GALVANOMETERS.

Principle of the Galvanometer—Detector Galvanometer—The Use of Long and Short Coil Galvanometers—Classification of Galvanometers—Relative Calibration of a Galvanometer—Tangent Galvanometer—Table XI. Natural Sines and Tangents—The Tangent of an Angle — Student's Combination Tangent Galvanometer—Directions for Setting up Student's Combination Galvanometer—Variation of Needle's Deflection with the Turns and Diameter of the Galvanometer Coil—Use of the Tangent Galvanometer as an Ammeter — Table XII. Tangent Galvanometer Constants — Thomson Mirror Reflecting Galvanometer—Astatic Differential and Ballistic Galvanometers—D'Arsonval Galvanometer—Questions.

178. Principle of the Galvanometer.—An instrument which measures a current by its electromagnetic effect is called a galvanometer. Galvanometers are used for detecting the presence of an electric current in any circuit, and for determining its direction, strength and pressure. Their construction is based on the principle that a magnetic needle, or its equivalent, is deflected when brought under the influence of a magnetic field, such as that of a wire through which a current is flowing. A simple galvanometer consists essentially of a magnetic needle poised or suspended in the centre of a coil of wire, and provided with a circular scale, graduated in degrees, on which the deviation, or deflection, of the needle may be noted. When such an instrument is connected in a circuit the presence of the current is shown by the deflection of the needle. The direction of the current is shown by the

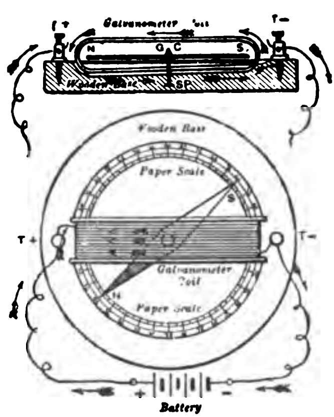


Fig. 152.—Simple Galvanometer.

side towards which the **N**-pole of the needle moves, ¶ 168. The strength of current is indicated by the amount of the needle's deflection; since the position the needle takes up depends upon the relative magnitude of the magnetic forces, due to the current and the earth. The earth's magnetism may be considered to be approximately constant at any particular place.

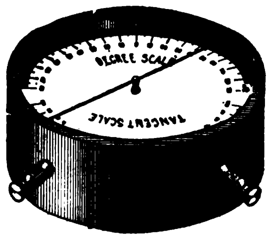


Fig. 153.—Student's Detector Galvanometer.

To obtain the maximum effect of the current's field, the galvanometer wire or coil, when no current is flowing, is arranged parallel to the magnetic needle when it is at rest, so that the plane of the coil passes through the axis of the needle and the magnetic meridian. *Galvanometers are usually set up to conform to the above conditions before sending a current through them;* the current's field will then act at right angles to the earth's field, and the position the needle will take up when the current flows is the resultant of these two forces. A certain amount of the current's field is therefore used to overcome the earth's attraction for the needle before it moves at all. When the needle is deflected to 90 degrees, or at right angles to the wire, it is in the maximum position of the current's field. The value of the deflection is dependent upon the current flowing through the coil, but is not proportional to the current; that is, if one current produces twice the number of deflections of another current the former is not of twice the strength, ¶ 182. With the needle parallel to the coil, or at the zero scale position, a small current deflects

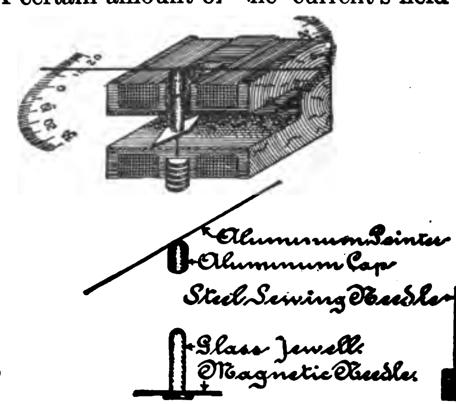


Fig. 154.—Construction of Student's Detector Galvanometer.

it considerably, but as the angle the needle makes with the coil increases, a much greater magnetic force is required. For example, it requires a greater force to deflect the needle one degree from the 45-degree position than to deflect it one degree from the 15-degree position. The galvanometer coil may be wound with a great many turns of fine wire, in which case the instrument is said to be sensitive; that is, the needle is appreciably deflected by a very small current; or it may be composed of a few turns of very heavy wire, in which case it is intended for use with large currents.

By the *sensibility of a galvanometer* is meant the amount of current required to produce a given deflection. The sensibility is sometimes rated in ohms. For example, a galvanometer with a sensibility of 2 megohms, ¶ 126, means that if it is connected in series with 2 megohms and a potential of 1 volt applied to the circuit, the movable system will be deflected one division of the scale. The sensibility of a galvanometer, therefore, depends upon the number of times the current circulates around the coil, the distance of the needle from the coil, the weight of the needle, and the amount of friction produced by its movement. The needle is usually quite small, and often a compound one. See ¶ 187. In very sensitive galvanometers the coils are wound with thousands of turns of very fine wire, and shunts are generally used in connection with them.

179. Detector Galvanometer.—

A student's detector galvanometer is illustrated in Fig. 153, and the sectional parts in Fig. 154. A circular glass-covered box contains the magnetic system inclosed in a rectangular coil of finely wound wire. An aluminum pointer is fixed to an aluminum cap, Fig. 154, and the magnetic needle fastened to a glass jewel. The cap telescopes the jewel and the pointer is arranged at right angles to the needle. One-half of the dial is graduated in degrees and the other half in divisions corresponding to the tangents of the various angles, ¶ 184. In adjusting this instrument for use, turn the box around till the pointer is directly over the zero mark on the scale; the pointer will then point east and west, and the magnetic needle at right angles to it will be in the magnetic meridian, as will also the coil of wire. The coil is wound with No. 30 B. & S. magnet wire, and has a resistance of about 30 ohms. The instrument is very sensitive; a current of about .00001 ampere will deflect the needle 1 degree.

180. The Use of Long and Short Coil Galvanometers. In making electrical measurements it is necessary to use current. Suppose it is desired to measure the resistance of

the cotton insulation around a piece of wire, Fig. 155; a current must be passed from the sheet of tin foil wrapped around the insulated wire, through the cotton insulation to the wire itself. The value of this current is to be noted on the galvanometer. The current will be very small that flows through, say one-eighth inch of cotton, so that the galvanometer must be extremely sensitive to record such a minute current, therefore the coil should be small in diameter and wound with many turns of very fine wire, and the needle arranged to eliminate as much friction as possible. On the other hand, suppose it is desired to indicate the current flowing through a number of incandescent lamps if a fine wire or long coil galvanometer is connected in series with the lamps; either the resistance would be so high that the lamps would not light, or the coil would be heated and destroyed, due to an excessive current passing through it, ¶ 257. A short thick coil galvanometer of a large diameter, containing one or more turns, and consequently very low resistance, is suitable for this case. The total magnetising force deflecting the needle may be the same as before, but produced by a large current circulating around a few turns instead, of a small current, around thousands of turns, ¶ 197.

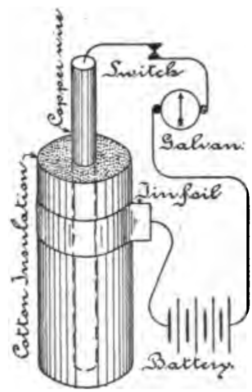


Fig. 155.—Measuring Insulation Resistance.

Long coil galvanometers of very high resistance are used to measure electrical pressure, and when properly standardized their scales are graduated directly in volts and the instrument then becomes a *voltmeter*, ¶ 233. The standardization consists in experimentally determining the position of the needle, when the coil is subjected to different known pressures, and marking these values on the scale; the process is called *calibration* and the galvanometer is calibrated absolutely as a direct reading instrument. It is still the current that deflects the needle, and its strength is dependent upon the pressure. Short coil galvanometers of very low resistance have their scales calibrated to read directly in amperes, and thus become amperemeters or *ammeters*, ¶ 203.

181. Classification of Galvanometers.—According to the

principle of action, galvanometers may be divided into two classes; first, those in which the magnet or magnetised body is arranged to move and the coil held stationary, and second, those in which the magnet is stationary and the coil arranged to move. Each class is largely used in practice for laboratory and commercial purposes, and constructed in a variety of forms. In construction, the winding used may be "*long coil*" or "*short coil*," and the method of supporting the magnetic system either by suspension, by poising it, or by delicate springs. The deflections may be noted either by a pointer attached to the magnetic system and moving over a graduated scale, or by a small mirror attached to the system. A ray of light focused upon the mirror is reflected upon a scale at some distance and greatly enlarges a small movement of the magnetic system. In another method the image of the scale deflection is observed on the mirror by a telescope located at about the same distance as the scale, ¶ 189. Long coil galvanometers may be used as short coil galvanometers when a shunt is employed, ¶ 162.

182. Relative Calibration of a Galvanomter.—

Exp. 56: Shunt the detector galvanometer, ¶ 162, with about 4 feet of No. 18 magnet wire and connect the shunted instrument in series with the gas voltameter, ¶ 120, and a source of E. M. F. Allow the current to pass for about five minutes and note the average deflection of the needle. (Find the average deflection by dividing the sum of all the readings, taken at one-half minute intervals, by the number of readings so taken.) Calculate the current by Formula (7), corresponding to the average deflection it produced, and place results in table for comparison. Repeat a number of such tests and calculations, using each time a different E. M. F. In such a test the following results were obtained from the calculations for a particular shunted galvanometer:

Degrees.	Amperes.
25	0.5
35	0.75
40	1.0
45	1.05

The above shunted galvanometer is said to be *calibrated relatively*. Suppose that when it is used in another circuit with the same shunt, the deflection produced by an unknown current is 30 degrees, then by reference to the table the approximate current will be .62 ampere, since .5 ampere produces 25 deflections and .75 ampere, 35 deflections. That the deflections are not proportional to the current is also shown

by this test. If a new scale were made for the instrument and .5 ampere substituted for the 25 degree mark and so on, then we would have an *absolute calibration* of the instrument, or practically, a shunted ammeter, ¶ 209.

Exp. 57: Connect a rheostat of several hundred ohms in series with the detector galvanometer, ¶ 179, to one Daniell cell, assumed to give 1 volt E. M. F., and record the deflection corresponding to this pressure. Make a number of tests, using each time a different number of cells connected in series, and tabulate results as below:

Deflections.	Volts.
17	1
30	2
40	3
45	4

The galvanometer is now *relatively calibrated as a voltmeter*. Suppose a dry cell, when connected to the galvanometer and extra resistance in series, gives 21 deflections; then its E. M. F. is between 1 and 2 volts, approximately 1.4 volts by proportionate calculation from the test. The calibration could be made absolute, as in Exp. 56.

183. Tangent Galvanometer.—The tangent galvanometer is so called because a particular function of each angle of the needle's deflection, called a tangent, is directly proportional to the current flowing through the instrument. There is, therefore, a direct law between the current and deflections when the instrument is properly constructed. The magnetic needle, which should be very small as compared with the diameter of the coil (for example, needle .75 inch, diameter of coil 8 inches), is poised or suspended in the centre of a coil of large diameter, of one or more turns, Fig. 158. In the centre of such a coil the magnetic field is practically uniform, Fig. 139. The axis of the needle is parallel to the coil when no current is flowing, both being, therefore, in the magnetic meridian.

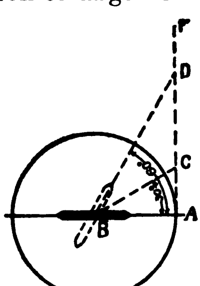


Fig. 157.—The Tangent of an Angle.

184. The Tangent of an Angle.—

Instead of measuring an angle in degrees of an arc, it may be reckoned by some function of the angle. In Fig. 157 the position of the galvanometer needle when pointing to zero on the circular scale is represented by the line AB. Draw an indefinite line, AF, perpendicular to AB, and tangent to the circle at point A. Suppose the needle is now deflected by the current to a point along the line BC, making the angle ABC of a certain number of degrees. The line, AC, is called the tangent of the angle ABC. The

value of the tangent of an angle (length of line AC) increases as the angle opens out or increases; thus, if another current deflects the needle along the line BD, making the angle ABD of so many more degrees, the tangent of this angle is represented in value by the length of the line AD. When the needle is deflected at right angles, or 90 degrees, the radius prolonged will not intersect the tangent line, or, the tangent of 90 degrees is infinity. The values of the tangents vary from 0 to infinity. If the value of the radius be unity, or one, the tangent of 45 degrees will be equal to one (that is, the length of line AB = AC), so that the value of the tangent of any angle less than 45 degrees will be less than one, and of a larger angle than 45 degrees more than one. The value of the tangents for each angle is given in the following table. For example, the tangent of 70 degrees is 2.7475, which means that if the length of radius AB is 1, the length of the line AC is 2.7475 times as great as the radius.

Table XI.—Natural Sines and Tangents.

∠	Sin.	Tan.	∠	Sin.	Tan.	∠	Sin.	Tan.	∠	Sin.	Tan.	∠	Sin.	Tan.
0°	.0000	.0000	18°	.3090	.3249	36°	.5878	.7265	54°	.8090	1.3764	72°	.9511	3.0777
			19	.3256	.3443				55	.8192	1.4281	73	.9563	3.2709
1	.0175	.0175				37	.6018	.7536	56	.8290	1.4826			
2	.0349	.0349	20	.3420	.3640	38	.6157	.7813				74	.9613	3.4874
3	.0523	.0524				39	.6293	.8098	57	.8387	1.5399	75	.9659	3.7321
			21	.3584	.3839				58	.8480	1.6003	76	.9703	4.0108
4	.0698	.0699	22	.3746	.4040	40	.6428	.8391	59	.8572	1.6643			
5	.0871	0875	23	.3907	.4245							77	.9744	4.3315
6	.1045	.1051				41	.6561	.8693	60	.8660	1.7321	78	.9781	4.7046
			24	.4067	.4452	42	.6691	.9004				79	.9816	5.1446
7	.1219	.1228	25	.4226	.4663	43	.6820	.9325	61	.8746	1.8040			
8	.1392	.1405	26	.4384	.4877				62	.8829	1.8807	80	.9848	5.6713
9	.1564	.1564				44	.6947	.9657	63	.8910	1.9626			
			27	.4540	.5095	45	.7071	1.0000				81	.9877	6.3138
10	.1736	.1763	28	.4695	.5317	46	.7193	1.0355	64	.8988	2.0503	82	.9903	7.1154
			29	.4848	.5543				65	.9063	2.1445	83	.9925	8.1443
11	.1908	.1944				47	.7314	1.0724	66	.9135	2.2460			
12	.2079	.2126	30	.5000	.5774	48	.7431	1.1106				84	.9945	9.5144
13	.2250	.2309				49	.7547	1.1504	67	.9205	2.3559	85	.9962	11.43
			31	.5150	.6009				68	.9272	2.4751	86	.9976	14.30
14	.2419	.2493	32	.5299	.6249	50	.7660	1.1918	69	.9339	2.6051			
15	.2588	.2679	33	.5446	.6494							87	.9986	19.08
16	.2756	.2867				51	.7771	1.2349	70	.9397	2.7475	88	.9994	28.64
			34	.5592	.6745	52	.7880	1.2799				89	.9998	57.29
17	.2924	.3057	35	.5736	.7002	53	.7986	1.3270	71	.9455	2.9042			

When it is desired to compare the relative strength of two currents, each is passed through the tangent galvanometer, properly set up, and the corresponding deflections noted. The first current will bear the same relation to the second current that the tangent of the first angle bears to the second angle. The value of the tangents is taken from the table. Calling I and I_1 the two currents to be compared and d and d_1 the deflections produced by these currents respectively, then:

I is to I_1 as tan of d is to tan of d_1,

$$\text{or} \quad \frac{I}{I_1} = \frac{\tan d}{\tan d_1} \quad \text{. . . . . (51).}$$

$$\text{Or} \quad I = \frac{I_1 \times \tan d}{\tan d_1}$$

Prob. 66: A tangent galvanometer is deflected 17° when inserted in series with a solenoid and a Daniell cell. When a Grenet cell is substituted the deflection is 31°. What is the relative strength of current through the solenoid when the Grenet cell is used?

By Formula (51) $I = \frac{I_1 \times \tan d}{\tan d_1} = \frac{I_1 \times .3}{.6}$, or $I = \frac{1}{2} I_1$, or the Grenet cell current was twice as strong as the current from the Daniell cell.

$d = 17°$, $\tan d = .3$, $d_1 = 31°$, $\tan d_1 = .6$.

Prob. 67: If one ampere deflects the needle of a tangent galvanometer 5° how many amperes will deflect it 50°?

From Formula (51) $I_1 = \frac{I \times \tan d_1}{\tan d} = \frac{1 \times 1.1918}{.0875} = 13.6$ amperes.

$I = 1$ ampere, $d = 5°$, $\tan d = .0875$, $d_1 = 50°$, $\tan d_1 = 1.1918$.

If a tangent galvanometer is constructed or adjusted so that one ampere deflects the needle 45°, since the tangent of 45° equals one, the value of any other angle of deflection will represent the value of the current in amperes passing through the instrument.

Fig. 158.—Student's Tangent Galvanometer.

185. Student's Combination Tangent Galvanometer.—

For many laboratory measurements the combination tangent galvanometer, illustrated in Fig. 158, may be used. It consists of the detector galvanometer (described in ¶ 179) placed in position in the tangent coil frame, 8 inches in diameter, constructed of hard wood and mounted on a suitable base. The detector galvanometer is readily removed from the frame so that it may be used separately when desired. When placed in position its needle is in the centre of the coils on the frame and the current is passed through the outer coils only. There are four coils of No. 18 wire wound on the frame with two turns per coil. The terminals of each coil are connected to binding posts; the figure shows the binding posts of two coils, the other four posts being on the opposite side. Three brass leveling screws underneath the base are used to level the instrument so that the glass jewel rides freely on its pivot.

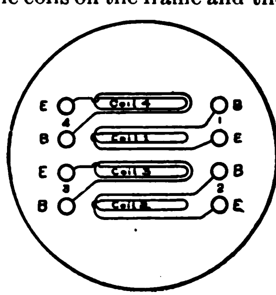


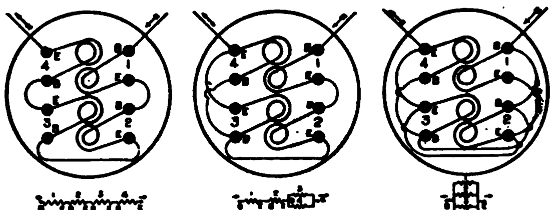
Fig. 159.—Method of Winding Coils in Student's Tangent Galvanometer.

Fig. 159 shows a diagram of the method of winding. The coils are all wound in the same direction, B representing the beginning of a coil and E its ending. The advantage of the separate coils is that they

may be connected up in a number of different ways to illustrate the law of series and parallel circuits, and the magnetic effect upon the needle by varying the number of turns around it. Figs. 160 A, B and C, illustrate several connections of the galvanometer coils, and the turns, or number of times the total current would flow around the needle are also given in each case.

186. Directions for Setting up Student's Combination Galvanometer.—

Seat the detector galvanometer on the horizontal support of the coil frame, Fig. 158, by means of the projecting wooden pin. Turn the frame so that it points N and S, with its plane in the magnetic meridian. You cannot see the magnetic needle directly underneath and parallel to the frame when it is at rest, and for this reason the pointer is fixed at right angles to it. Now revolve the detector gal-



A All Coils in Series—8 Turns. B. Two Coils in Series with Two in Parallel - 6 Turns. C All Coils in Parallel 2 Turns.

Fig. 160.—Connections of Coils in Student's Tangent Galvanometer.

vanometer on its wooden pivot so that the zero position on the scale lies directly underneath the pointer. Send a current through the four coils in series, and the deflection is, say 44° to the right; reverse the current, and if the deflection is 44° to the left, the needle and coil are in the magnetic meridian. If the latter deflection had been 48° then the coil frame must be moved a little in the opposite direction to that of the greater deflection, and zero position again adjusted to the pointer with no current flowing. This adjustment should be made until the needle deflects equally on both sides of the zero mark for the same strength of current. Deflections may be read from the degree scale of the instrument and the tangents obtained from the table, or the deflections on the tangent scale are directly proportional to the current. The resistance of the four coils connected in series is .165 ohm, and a current of 0.25 ampere sent through them will deflect the needle 45°.

187. Variation of Needle's Deflections with the Turns and Diameter of the Galvanometer Coil.—

Exp. 58: Send a current of known strength, say .5 ampere, around one coil of the galvanometer, ¶ 185, and note the deflection on the tangent scale. The current flows twice around the needle, since there are two turns per coil. Pass the same strength of current through two coils in series. The current flows four times around the

needle and it is deflected to a value on the tangent scale double that of the first case. If three coils are used in series the tangent scale value is tripled. Note also the degree scale deflections, and compare the value of the tangents taken from the table for each deflection.

The sensibility, ¶ 178, of the galvanometer is therefore directly proportional to the number of convolutions of wire on the coil. If the coil had been increased to twice the diameter and the same strength of current passed twice around it, the tangent of the angle of deflection would have been just one-half that produced by the same current flowing twice around the smaller coil; therefore, the sensibility is also inversely proportional to the diameter of the coil, decreasing the diameter, increasing the sensibility, and vice versa.

188. Use of the Tangent Galvanometer as an Ammeter. The value of any current sent through the tangent galvanometer may be calculated directly in amperes from the following formula, when the dimensions of the instrument are known. The needle is supposed to move in a horizontal plane and not controlled by any force but the earth's magnetism.

Let I = current in amperes;
r = *radius* of coil in inches;
N = number of turns in coil;
d = angle of deflection of needle;
H = a constant from the table below.

$$\text{Then, } I = \frac{H \times r}{N} \times \tan d \quad . . . . (52).$$

The constant, H, given in the following table represents the horizontal force of the earth's magnetism for the place where the galvanometer is used. It may be approximated for other localities not indicated. The values given were furnished by the U. S. Geodetic Bureau for the epoch 1900 and are for square inch measure. Each value has been multiplied by $\frac{2\pi}{10}$ so that Formula (52) is correct as given.

Table XII.—Tangent Galvanometer Constants.—Values of H.

Boston	.699	New Haven	.731
Chicago	.759	Philadelphia	.783
Denver	.919	Portland, Me.	.674
Jacksonville	1.094	San Francisco	1.021
London	.745	St. Louis	.871
Minneapolis	.681	Washington	.810
New York	.744		

Since the tangent of the angle of deflection in Formula (52) is always to be multiplied by a constant number, $\frac{H \times r}{N}$, for a particular instrument and place, this value is called the *constant of the galvanometer.*

To FIND THE CURRENT IN AMPERES FLOWING THROUGH THE INSTRUMENT.
Multiply the tangent of the angle of deflection by the galvanometer constant.

Let K = constant of the galvanometer $= \frac{H \times r}{N}$;

I = current in amperes;

d = deflection of needle.

Then, $I = K \times \tan d$ . . . . (**53**).

Prob. 68: A Daniell cell is connected to 4 coils of the student's tangent galvanometer connected in series, ¶ 154, and the needle is deflected 30 degrees. The diameter of the coil is 8 inches, and with 4 coils in series with 2 turns per coil, the total turns are 8. What current is flowing through the instrument if it is located in New York?

Fig. 161.—Thomson Mirror-Reflecting Galvanometer (single coil).

By Formula (52)

$$I = \frac{H \times r}{N} \times \tan d = \frac{.744 \times 4}{8} \times .5774 = .214 \text{ ampere.}$$

H for New York = .744, r = 4 inches radius, N = 8 turns, tan d = .5774.

Prob. 69: What is the constant of the galvanometer in Prob. 68?

$$K = \frac{H \times r}{N} = \frac{.744 \times 4}{8} = .372.$$

Prob. 70: A bichromate cell is connected to the galvanometer referred to in Probs. 68 and 69. What current flows through the instrument if the needle is deflected 50 degrees?

By Formula (53) $I = K \times \tan d = .372 \times 1.1918 = .443$ ampere.

K for the galvanometer = .372 from Prob. 69, tan d = 1.1918.

189. Thomson Mirror-Reflecting Galvanometer.—

In this type of instrument, Figs. 161 and 162, great sensibility has been attained by bringing the coil as close to the needle as possible and winding it with many turns of very fine wire. On the back of a small mirror, about ½ inch in diameter, are fastened by shellac, a number of magnetic needles with their N-poles in one direction. The mirror is suspended in the centre of the coil, so that the needles hang

Fig. 162.—Details of the Coil.

horizontally, by a fine cocoon silk fibre which extends the entire length of the vertical brass tube shown in Fig. 161. To facilitate the insertion of the magnetic system in the centre of the coil, it is wound in two sections, which are bolted together in the cylindrical brass box, leaving a small space between them through which the fibre suspension passes. The coil is completely enclosed from the atmosphere, which assists in rendering the instrument *dead-beat* in its action, *i. e.*, so that the magnetic system may come to rest almost instantly without first making a number of vibrations when the circuit is made and broken through the instrument. The pent up air produces a cushion effect upon the vibrating mirror, causing it to come to rest more quickly. The cylindrical box is mounted on a tripod, provided

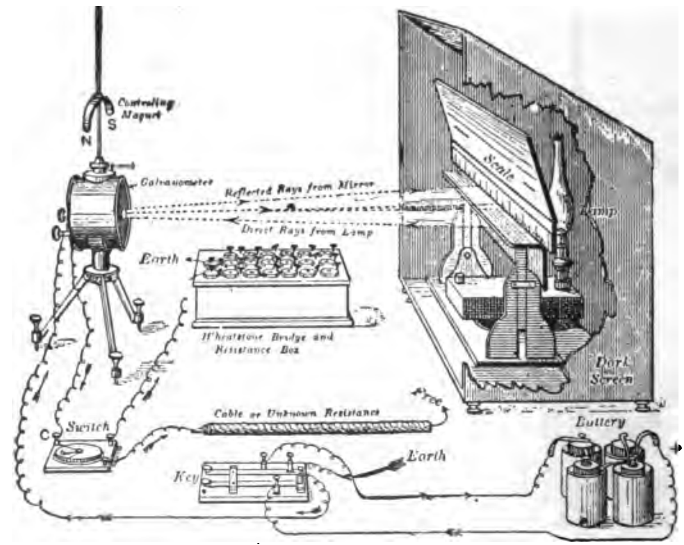


Fig. 163 —Thomson Mirror-Reflecting Galvanometer with Lamp, Stand, Scale and Connections of Apparatus for Measuring the Insulation Resistance of an Electric Cable.

with leveling screws, and can be rotated on its vertical axis. The curved controlling magnet, arranged on the vertical tube, can either be revolved, or raised and lowered, with regard to the magnetic needle. By turning it around the axis of the tube the mirror with its needle may be deflected to any position on the scale and the sensibility increased or decreased by raising or lowering the magnet, thereby increasing or decreasing its attraction for the needle. The instrument is most sensitive when placed with its coil in the magnetic meridian, with the controlling magnet elevated to such a position that its force upon the mirror's magnet just balances the action of the earth's attractive force upon the same.

A mirror reflecting galvanometer with its lamp, stand and scale, is shown in Fig. 163, and requires a darkened room for its operation.

A small vertical slit is cut in the lamp screen below the scale, and the ray from the lamp passing through this slit strikes the galvanometer mirror, which is about one yard distant. The galvanometer is adjusted so that the reflected beam of light strikes the scale. The zero position on the latter is located at the centre so that the beam swings to the right or left of zero, and is brought to zero position by the controlling magnet, or by twisting the fibre suspension by means of the knurled knob at the top of the tube. The angle between the original beam of light and the reflected beam will be twice the angle of the deflection of the mirror; the deflections of the spot of light on the scale, however, are practically proportional to the strength of currents through the instrument. When a telescope is substituted for the lamp, as in Fig. 164, a dark room is not required. The scale readings are reflected in the mirror and their value observed by means of the telescope.

Fig. 164.—D'Arsonval Mirror-Reflecting Galvanometer with Scale and Reading Telescope.

190. Astatic, Differential and Ballistic Galvanometers.

If two needles of equal strength are fastened to a vertical rod with like poles in opposite directions

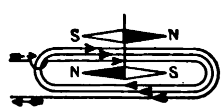


Fig. 165.—Connections of Single Coil Astatic Galvanometer.

forming an astatic needle, ¶ 58, and suspended, the earth's field has almost no directive force on the magnetic system. Since the earth's attraction for this needle has been thus neutralized, a much smaller current will deflect it than when the earth's directive force has to be overcome. This principle is used in increasing the sensibility of galvanometers. In Fig. 165, the galvanometer coil surrounds the lower needle and the direction of current between the two needles tends to turn them the same way. This method is used in the astatic galvanometer, Fig. 166, which is

Fig. 166.—Single Coil Mirror-Reflecting or Direct Scale Astatic Galvanometer.

arranged so that the deflections may be read from the circular scale or the instrument may be used as a mirror-reflecting galvanometer, by means of the small mirror attached to the vertical fibre suspension A controlling magnet is also provided to bring the needle system to zero and alter its sensibility. A coil sometimes surrounds each needle as shown in Fig. 167, in which case they are connected so that the direction of current in both coils will tend to turn the system in the same direction.

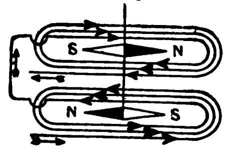


Fig. 167.—Connections of Double Coil Astatic Galvanometer.

The Thomson mirror-reflecting astatic galvanometer, Fig. 168, is so constructed. The instrument is illustrated with the front swung open so that each half of each coil, as well as the astatic system, may be noted. The needles are compound and fastened to a small mica disc and rigidly joined together by a fine glass rod; midway between the needles is fastened the mirror, mounted on a mica vane and secured to the glass rod. The mica vane assists in damping by fanning the air when the needles are deflected. The whole system is suspended by a cocoon fibre attached to the upper end of the glass rod and extending through and protected by the vertical brass tube. When the door is closed the mirror may be seen through a glass window. Binding posts are provided for the terminals of each coil and the coils may be connected in series, parallel, etc., care being exercised to have the direction of current as given in Fig. 167. The coils of each needle may be used separately for comparing two different current strengths at the same time, when the direction of the current in each is such as to tend to turn the mirror oppositely. When so used the instrument is called a *differential galvanometer*.

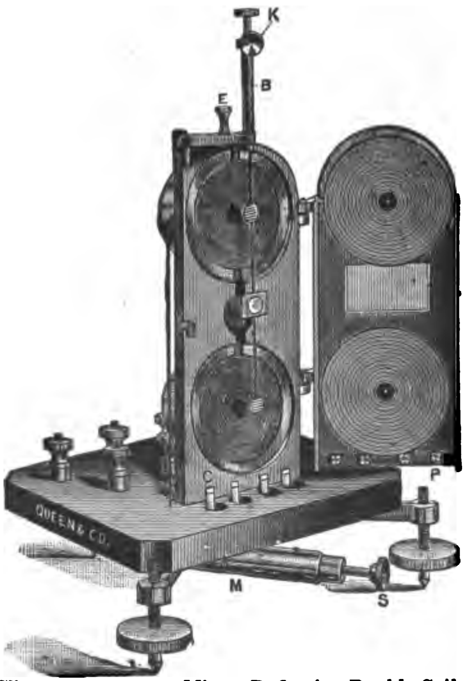


Fig. 168.—Thomson Mirror-Reflecting Double Coil Astatic Galvanometer with Case Open.

In a special form of mirror reflecting galvanometer called a *ballistic*

galvanometer, used for measuring momentary currents (as induction currents or the discharge of a condenser, ¶ 303), the magnetic system is constructed so as to have considerable weight, and arranged to give the least possible damping effect. If a momentary current be passed through its coils, the impulse given to the needle does not cause appreciable movement of the magnetic system until the current ceases, owing to the inertia of the heavy moving parts, the result

Fig. 169.—D'Arsonval Mirror-Reflecting Galvanometer.
Vertical magnet form.

Fig. 170.—D'Arsonval Mirror-Reflecting Galvanometer.
Horizontal magnet form.

being a slow swing of the needle. The maximum deflection is noted on the scale just at the point where the system ceases to move and begins to swing back to zero.

191. D'Arsonval Galvanometer.—This galvanometer, illustrated in Figs. 169 and 170, is an example of that class in which the magnet is large and stationary, and the galvanometer coil small and free to move, when a current is sent through it. A coil of wire wound upon a rectangular bobbin is suspended by fine silver wires between the poles of a laminated horseshoe magnet, so that the horizontal axis of the coil is at right angles to the magnetic lines of force between the

poles of the magnet. When a current is led to and from the coil by means of the suspension wires above and below it, the coil becomes a magnetic body, and tends to turn so that its lines of force will be in the same direction as those of the permanent magnet field. This tendency to rotate is opposed by the torsion of the suspension wire. The coil will move to the right or left, depending upon the direction of current through it. A stationary piece of soft iron is arranged in the centre of the coil and supported from the back, its purpose being to increase the strength of the magnetic field in which the coil moves. By properly shaping the pole pieces the magnetic field may be so varied that the deflections will be directly proportional to the current.

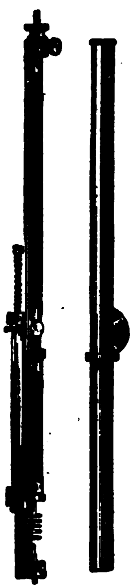


Fig. 171.—Details of Removable Suspension Coil and Tube.

If the coil is wound upon a non-magnetic metallic frame, the instrument is very dead-beat, as the instant the coil moves induced currents are set up in the coil frame, and are in such a direction as to tend to stop its movement, ¶ 292. A mirror is attached to the coil so that the instrument may be used with a telescope and scale, Fig. 164; or a pointer may be added, fixed at right angles to the mirror and made to sweep over a circular scale attached to the magnets. Another form of D'Arsonval galvanometer is shown in Fig. 170, in which the magnets are horizontal. The coil is suspended in a brass tube containing a window, opposite the mirror. The tube is clamped in position between the specially shaped pole pieces and can be readily removed and replaced by another of higher or lower resistance, as desired. Details of the tube and its casing are shown in Fig. 171. The system is suspended by a phosphor bronze strip, and the coil can be adjusted by turning the knurled knob at the top of the tube. A fine spring at the bottom serves to lead the current from the coil and oppose its motion. The advantage of this type of instrument over that of the Thomson form is, that it is not affected by the earth's or other external magnetic fields, so that it may be used in close proximity to dynamos. This principle is used in the construction of the Weston instruments, ¶¶ 208 and 235.

QUESTIONS.

1. State how you would proceed to measure the current flowing through a number of incandescent lamps with a long coil, high resistance galvanometer.

2. The sensibility of a certain galvanometer is four megohms. What is meant by this statement?

3. Give two general classifications of galvanometers: first according to the principles employed in their construction; second, according to their construction.

4. Upon what factors does the sensibility of a galvanometer depend?

5. Why is it necessary to construct such very sensitive instruments?

6. What is meant by the absolute calibration of a galvanometer?

7. What advantage does a dead-beat galvanometer possess over one that is not so constructed?

8. Explain the difference between a differential and a ballistic galvanometer.

9. Give three methods of damping the needle of a galvanometer.

10. How would you arrange a low resistance sensitive galvanometer so that it could be used for measuring electrical pressure?

11. Explain how a galvanometer can measure electrical pressure, since the deflection of its magnetic system is dependent upon the strength of the current actuating it.

12. What are the advantages of a D'Arsonval galvanometer?

13. Make a sketch of a double coil astatic galvanometer with the coils joined in parallel. Show the direction of current around the needle, and indicate the direction in which the system will be deflected by the current.

14. Why is an astatic galvanometer more sensitive than one with a single needle?

15. An unknown current deflects the needle of a tangent galvanometer 27 degrees; the galvanometer constant is .65. What is the strength of current in amperes flowing through the instrument? *Ans.* .33 ampere.

16. In question 15 how many amperes will deflect the needle of the galvanometer 38 degrees? *Ans.* .507 ampere.

17. A current of 5 amperes is sent through the galvanometer in question 15. What will be the corresponding deflection of the needle? *Ans.* 82°.

18. Make a diagramatic sketch of the coils of the student's galvanometer, similar to those depicted in Fig. 160, when it is connected: (1) two coils in series, two groups in parallel; (2) one coil in series, with two in parallel and the remaining coil in series with them.

LESSON XVII.

ELECTROMAGNETS.

Magnetisation of Iron and Steel by an Electric Current—Magnetic Field of an Electromagnet—Attractive Force of a Solenoid for an Iron Core—Magnetic Circuits—Typical Forms of Electromagnets, their Construction and Use—Magnetomotive Force—Calculation of Magnetic Circuits—Table XIII. Coarse and Fine Wire Electromagnets—Testing the Attractive Force of an Electromagnet—Magnetisation Curve—Tractive Force of an Electromagnet—Questions.

192. Magnetisation of Iron and Steel by an Electric Current.—

Exp. 59: Wind a number of turns of insulated wire around an iron bar, Fig. 172, and send a current through the wire. Plunge the bar into iron filings, and it attracts them mostly at the ends, and when the current is interrupted the filings drop off. Test the polarity of each end of the bar with a compass. Note that upon looking at the end of the bar which repels the N-pole of the compass the current flows around the winding in the opposite direction to that in which the hands of a watch move, Fig. 172. When viewing that end which attracts the N-pole of the compass, the current flows around the wire in the direction that the hands of a watch move. Figs. 172 and 173 illustrate the polarities of a steel bar, according to the clock rule, for all possible changes in either the direction of current or the direction of winding with a given direction of current.

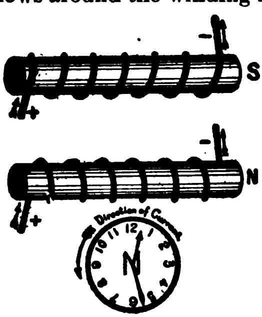


Fig. 172.—Current Anti-Clockwise—N-Polarity.

Exp. 60: Remove the bar from the coil and note that the polarity of each end of the helix is the same as with the bar inside of it; the magnetism was, however, much stronger when the bar was inserted in the coil. If suspended or poised, see Fig. 148, the helix and its iron core will take up a position in the earth's field similar to the helix or compass needle. It will also attract or repel the poles of a like helix and core according to the law of attraction and repulsion.

When a piece of hard steel is placed in the vicinity of an electromagnetic field, many of the lines of force of the field

are bent out of their natural direction and converge into the steel. There are now more lines of force passing through the space occupied by the steel than when this space was occupied by air alone. *The capability of any substance for conducting magnetic lines of force is termed its permeability*, therefore the permeability of the steel is much greater than that of air. When a piece of soft iron is substituted for the steel, even more lines of force will pass through the same space, showing that the permeability or conducting power of iron is greater than that of steel. The permeability of iron may be as high as 2000 times that of air, or 2000 times as many lines of force will pass through space when occupied by iron as when it is occupied by air. An iron bar inserted in a helix or solenoid is a much better conductor of the magnetic whirls inside the solenoid than the air, so that the strength or attractive force of the solenoid is materially increased, though the magnetising current is the same as before. *An iron core introduced into a solenoid carrying a current becomes strongly magnetised, and is called an electromagnet.* The direction of the lines of force through the iron core of the solenoid is the same as their natural direction through the solenoid alone, so that all the laws for polarity of the solenoid given under electromagnetism, Lesson XV, apply also to an electromagnet. By applying the principle of the molecular theory of magnetism, ¶ 26, the phenomenon of magnetism in the iron bar produced by the magnetic effect of the current will be understood. The current's natural magnetic field acts inductively upon the molecules of

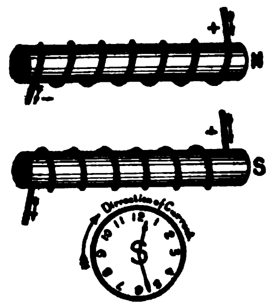


Fig. 173.—Current Clockwise—S-Polarity.

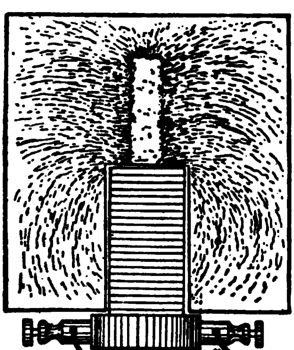


Fig. 174.—Magnetic Field of a Solenoid and Core.
Made with iron filings on a horizontal piece of cardboard.

the iron bar, causing them to change the relation of their internal magnetic circuits with respect to each other. thus producing an external field near the ends of the core, very much in the same way that a permanent magnet acts on them. The current's magnetic field simply makes evident the latent magnetism of the iron. This molecular action also accounts for the permanent magnetism produced in a piece of steel inserted in a solenoid after the current ceases, since the internal molecular friction prevents many of the molecules from resuming their original positions.

193. Magnetic Field of an Electromagnet.—The graphical field of a solenoid and core, or straight bar electromagnet, would be similar to that of a solenoid alone, as in Fig. 151, except that the filings would be attracted more closely together, illustrating the greater density or number of lines of force due to the iron core. A compass needle, used to explore the field, will take up the same position as with the solenoid alone, but it is now affected at a much greater distance. The magnetic lines of force emanate from the **N**-pole of the bar electromagnet, and completing their path through the external medium enter the magnet again at its **S**-pole. If the iron core of the solenoid be pulled out somewhat from the coil and a field made, the magnetic lines are conducted further away from the coil before returning to it, as in Fig. 174. The polarity is still the same as before, but the poles are not so strong as when the whole internal field of the solenoid was composed of iron.

194. Attractive Force of a Solenoid for an Iron Core.—When under the attractive influence of a solenoid, an iron bar is subjected to a pull, the magnitude of which depends upon the relative position of the two bodies and the magnetising current. If either body is free to move, and the force sufficiently strong, it will move to accommodate through itself the greatest possible number of lines of force. This attractive force may be weighed by arranging the core upon one end of a balance arm, with the solenoid directly below it, and placing weights in the scale pan to balance the force of the current's field upon the iron. While balanced, as in Fig. 175, test the polarity of the bar by a compass, and it is magnetised by induction, ¶ 36, with the polarities as shown. Note that part of the magnetic lines from the solenoid complete their circuit through the core, entering at its upper end,

which is consequently **S**-polarity (**S** where lines enter), they emanate from the lower or **N**-end and pass through the coil. Place the solenoid nearer to the core, or lower the core to it, and the pull is considerably increased, as noted by the additional weights required to be added to balance the current's attractive force. The strongest pull will take place when the middle of the iron core *nearly* coincides with the middle of the solenoid, as when they coincide the greatest number of the current's magnetic lines are accommodated through the core. The term "sucking coil" is sometimes applied to the solenoid when used in such connection with its core. This principle is extensively used to operate the feeding mechanism in arc lamps, Fig. 177; to automatically open switches in electric circuits when the current becomes excessive, as in the circuit breaker, Fig. 176, and in commercial instruments for measuring current and pressure, as in Fig. 191.

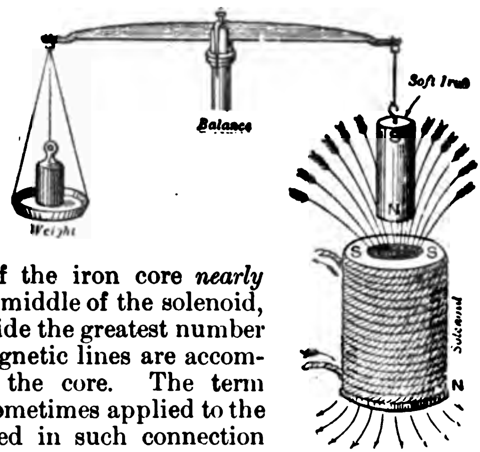


Fig. 175.—Weighing the Magnetic Attraction of a Solenoid for its Iron Core.

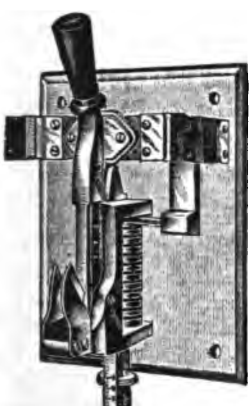


Fig. 176.—Automatic Circuit Breaker.

When the current becomes excessive the magnetic field of the few series turns of wire attracts a solenoid which releases a spring and the switch opens.

195. Magnetic Circuits.—A simple magnetic circuit, ¶ 42, of uniform cross-section is represented by the solid iron ring in A, Fig. 178, around which a number of turns of insulated wire have been wound. The direction of the current and resulting polarity of the coil is shown, while the arrows indicate the direction of the lines of force around the ring, which is the same as that in which the

hands of a watch move. If a ring, so magnetised, be plunged into iron filings it will not show any external poles, since the magnetic lines have a complete circuit through the iron. When a small air-gap is made by sawing out a small section of the ring, B, Fig. 178, a *compound circuit* is formed, and the lines of force are compelled to pass through the air gap to complete their circuit, so that a strong **N** and **S**-pole is produced where the cut has been made, and the space is permeated with lines of force. The lines of force through the iron circuit are not nearly so dense as before, since the resistance of the circuit has been increased, and with the same magnetising force the magnetic lines diminish as the resistance of the circuit increases, just as in an electric circuit the current decreases when with a constant pressure the resistance is increased. If the removed section of the ring is now replaced and the ring again plunged into iron filings while the core is magnetised, a great many filings will be attracted at the two joints, thus illustrating *magnetic leakage*. The density in the ring is not now so great as when it was solid, since the joints offer opposition to the magnetic lines, as is shown by some lines being forced through the air across the joint. A ring with two poles **is shown** in C, Fig. 178, the winding being in the same direction throughout the ring, and the ends of the wire being joined together. Current is passed in from any point and flows around each half of the ring in an opposite direction to a diametrically opposite point and then back to the battery. The arrows indicate the direction of current and magnetic lines of force, from which it will be seen that a *consequent* **N**-pole is produced at the top of the ring and a **S**-pole at the bottom. The lines of force complete their path through the air from pole to pole, as will be noted by plunging the ring into iron filings.

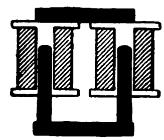


Fig. 177.—Pair of Solenoids with Iron Yoke and U-Shaped Movable Core.

Fig. 178.—The Magnetic Polarity of an Iron Ring.

Exp 61: Connect a horseshoe electromagnet, Fig. 179, with a source of current so that the limbs are like poles. Attract the keeper and then plunge the magnet into iron filings. One pole is produced in the centre of the keeper and the opposite pole in the bend of the horseshoe. The magnetic distribution is similar to the solid ring with two poles in C, Fig. 178.

196. Typical Forms of Electromagnets, Their Construction and Use.—If the bar electromagnet, Fig. 172, is bent around into a U shape, as in the right-hand view of Fig. 179, it forms a horseshoe electromagnet, thereby increasing the attractive power, ¶ 18. Instead of winding the insulated wire directly upon the core it is generally wound upon a wooden or brass bobbin several layers deep, which is then slipped over the soft iron horseshoe core, as in the left hand view of Fig. 179. The spools are then connected by wires so that the current will flow around each spool in the opposite direction, as viewed from the end of the core, when the limbs will have opposite polarity, Fig. 180. The attractive force of the magnet may be tested by means of a keeper of the same cross-sectional area, provided with a handle or hook and is found to be quite strong between the poles of the electromagnet. Instead of a forged horseshoe it may be composed of three parts, as in Fig. 180, where the two iron cores or limbs are connected by an iron yoke of equal cross section and secured by machine screws. The direction of current and resulting polarity are also illustrated.

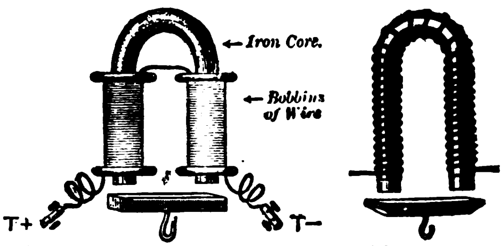


Fig. 179.—Horseshoe Electromagnets with Keepers.

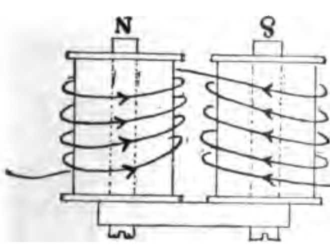


Fig. 180.—Direction of Current Around Horseshoe Magnet.

Horseshoe electromagnets are used in many practical applications of electricity, as in electric bells, automatic gas lighting burners, electric locks, etc., and are designed and con-

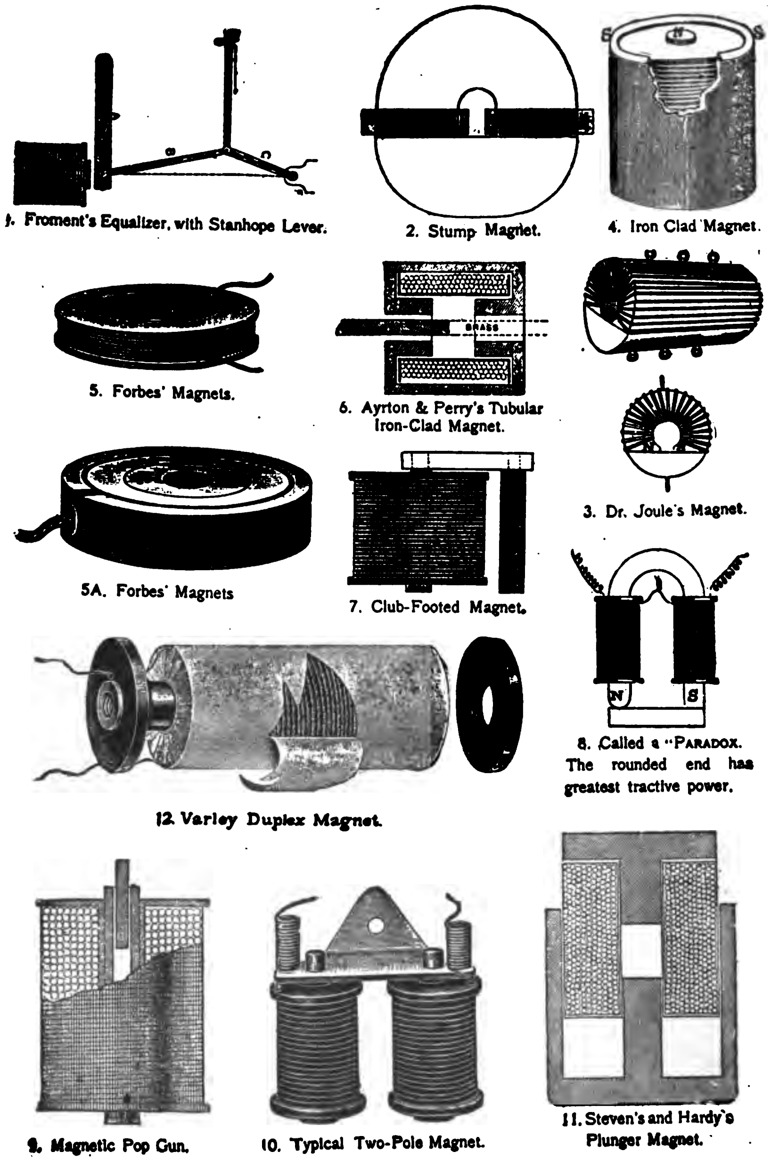


Fig. 181.—Typical Forms of Electromagnets.

structed to meet special requirements, according to the particular work to be performed by them. When it is desired to construct an electromagnet that will respond quickly to a current of short duration, as in bells and telegraph sounders, the bobbin windings and cores are made as short as possible. To give a very powerful attraction at a short distance, a short cylindrical bar magnet surrounded by an outer iron tube and united at the bottom by an iron yoke, No. 4 and 5 A of Fig. 181, is a good form; the iron jacket forms a return path for the lines of force and the poles are concentric. This type is known as an ironclad electromagnet, and is adapted for lifting purposes in factories, etc., since the windings are well protected and not liable to be injured by rough usage. To attract iron across a wide air gap requires a horseshoe electromagnet with comparatively long limbs to accommodate the windings, because it requires a great many turns of wire to provide sufficient exciting power to drive the lines of force through the air. To obtain a gentle pull over a long range, a solenoid or long tubular coil and a long movable core is used, as in Figs. 175, 177, and No. 6 and 11 of Fig. 181. For nearly all purposes the iron parts, including the yoke and keeper, should be arranged to form as nearly as possible a closed magnetic circuit, as in No. 2, Fig. 181.

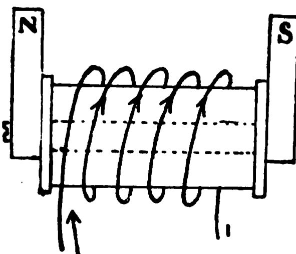


Fig. 183.—Electromagnet with the Coil on the Yoke.

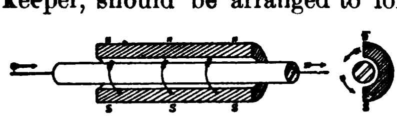


Fig. 184.—Straight Wire Electromagnet.

In No. 7 of Fig. 181, the winding is contained on a bobbin mounted on one spool. As much wire is required as if two spools were used, but one bobbin is saved. To be efficient the wire should be close to the iron core so that it may be brought under the inductive influence of as many of the current's magnetic whirls as possible. In Fig. 183, the solenoid is slipped on to the yoke, which is provided with short, stumpy pole pieces, for some specific purpose. A magnet with a slightly rounded or chamfered pole has an increased attractive power, since the lines of force become

very dense at the pole when they are thus slightly reduced, No. 8 of Fig. 181. In the electromagnet, No. 12 of Fig. 181, bare wire is used for winding, instead of insulated wire, but between each convolution is wound a silk or cotton thread to insulate the turns. The wire and thread are wound simultaneously by a specially constructed machine and known as Varley duplex winding. The layers are insulated from each other by paper; the advantage being that since the thickness of the insulation between the adjacent turns is greatly reduced by this method, many more turns per layer may be obtained than with ordinary winding, thus producing a greater magnetising force. To produce magnets of equal strength one-third of the weight of copper is saved by using the duplex winding in comparison with the ordinary winding.

A simple straight wire electromagnet is shown in Fig. 184, the indicated polarity of which should assist in fixing clearly in the student's mind the direction of the magnetic whirls of a straight wire. A piece of one-eighth inch diameter iron gas pipe is sawed into two equal sections lengthwise and a straight wire carrying a current is placed in one section, as shown in Fig. 184.

197. Magnetomotive Force.—

Exp. 62: Connect the coils of an electromagnet wound with many turns of wire in series with another magnet wound with a few turns of wire and join them to a battery. Plunge each magnet into iron filings. The magnet wound with many turns attracts more filings, yet since they are in series the current strength is the same through each magnet. The magnetism depends upon the turns, as well as upon the current strength.

Exp. 63: Note the number of pounds required to detach a keeper from the poles of its magnet when the spool is wound with 400 turns of fine wire and 1 ampere is passed through it, say 18 pounds is required. Now substitute another spool wound with 40 turns of much larger wire through which 10 amperes are sent. The keeper is detached by a force of 18 pounds as before.

From the above experiments it will be seen that the magnetism depends upon the turns, as well as upon the current strength; the current and turns together acting as a *magnetising force*. The magnetising force of a solenoid or any coil of wire is, therefore, equal to the product of the current expressed in amperes and the number of turns of wire, the product being called *ampere-turns*.

To Find the Total Magnetising Force of a Coil in Ampere-Turns:

Multiply the number of turns upon it by the strength of current passing through it.

For example: four amperes circulating 25 times around a coil produce a magnetising force of 100 ampere-turns. The same force could be produced by 2 amperes and 50 turns, or 100 amperes and 1 turn, etc., the product of the turns and current in each case being 100.

Let $I =$ current in amperes;
$T =$ number of turns.

Then,

$$\text{Magnetising Force} = I \times T \quad \ldots\ldots\ldots \quad \textbf{(54)}.$$

$$\text{Also } I = \frac{\text{Magnetising Force}}{T} \quad \ldots\ldots\ldots \quad \textbf{(55)}.$$

$$T = \frac{\text{Magnetising Force}}{I} \quad \ldots\ldots\ldots \quad \textbf{(56)}.$$

The term Magnetomotive Force is applied to the total magnetising force acting on the magnetic circuit, and for any magnetic circuit is *proportional* to the current and the number of turns in the solenoid; that is, the *ampere-turns* as shown above. But in order to adapt all results to terms of standard units, it becomes necessary to introduce other factors. It has been found by experiment that one ampere-turn sets up nearly 3.2 lines of force through an *air-path* one inch long and one square inch in cross-sectional area. Thus, if we had a solenoid of 50 turns and a current of 2 amperes flowing through it, nearly 320 units of magnetic pressure would be developed. The relation may be expressed in the following formula: Magnetomotive Force (M. M. F.)$=3.2\times I\times T$.

The magnetomotive force is sometimes conveniently expressed as the magnetomotive force per unit length of the coil or solenoid, which would be the intensity of magnetomotive force at any point, and represented by the letter H. This is easily found by dividing the total magnetising force; that is, the magnetomotive force by the total length l. Therefore, $H=3.2\times I\times T\div l$, where l equals length of solenoid. The above is only true for a solenoid in *air* or in other *non-magnetic* substances. The *total number of lines of force* produced in a solenoid is found by multiplying the sectional area of the magnetic circuit in square inches by the value of H.

For example: suppose we have a coil of 25 turns, the coil being bent into a circular shape to form a complete ring, so there will be no free poles. Each line of force would have a complete path inside the coil, so that the length of the magnetic circuit can easily be measured. A current of 20 amperes flowing through the coil would give by Formula (54) a magnetising force in *ampere-turns* of 500. If

the mean length of the magnetic circuit is 5 inches, then, the magnetomotive force per unit length, $H=3.2\times500\div5=320$, meaning that a uniform magnetic field is produced in the solenoid of 320 lines of force per square inch of sectional area. If the sectional area of magnetic circuit is .8 square inch, there is a total number of 256 lines of force produced in the coil, $.8\times320=256$.

198. Calculation of Magnetic Circuits.—All magnetic substances offer some opposition to the passage through them of magnetic lines of force. This opposition is termed *reluctance.* The *total number* of lines of force set up in a magnetic substance is termed *magnetic flux.* It is, practically, the TOTAL INDUCTION set up in a magnetic circuit by the magnetising force. *Magnetic flux*, or total number of lines of force, is treated as a *magnetic* current flowing in the magnetic circuit.

The calculation of the magnetic flux, which we will represent by the letter N, is similar to the calculation of current in an electric circuit by Ohm's Law. In an electric circuit the rate of flow in amperes of the electric current, equals the E. M. F. ÷ resistance; in a magnetic circuit, the rate at which magnetic lines of force pass through it, is equal to the M. M. F. ÷ reluctance, or,

$$\text{Magnetic Flux (N)} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}}$$

It is sometimes necessary to specify the density of the lines of force at any given point, or, the number passing through a unit area measured at right angles to their direction, which is termed the *magnetic density* or *magnetic induction* of the substance, and represented by letter B. If the total number of lines of force, or magnetic flux N is known, $B = N \div A$, where A would be the area of cross-section in square inches of the substance. It has been shown in ¶ 197, that the magnetic density produced in *air* by a solenoid depends entirely upon the intensity of magnetomotive force. The magnetic density or induction B, produced in a *magnetic* substance when placed in a solenoid, depends upon one other factor, namely, the *permeability* of the substance, ¶ 192.

The permeability of a magnetic substance is the ratio of the magnetic density, B, in the substance to the intensity of magnetomotive force, H, acting upon the substance; that is, $B\div H$=permeability of any magnetic substance. The symbol for permeability is the Greek letter μ (pronounced mu.) If the value of μ and H are known,

the magnetic density B can also be found by multiplying value of μ by value of H.

The reluctance of a magnetic circuit depends upon three quantities: the *length* of the circuit, the cross-sectional *area* of the circuit, the *permeability* of the substance which forms the circuit. If we let R represent reluctance, l the length of magnetic circuit in inches, A the sectional area of the circuit in square inches, and μ the permeability of substance constituting the circuit, then

$$R = \frac{l}{A \times \mu}$$

The magnetic circuit is usually a compound one; that is, one composed of two or more substances. It is, therefore, necessary to calculate separately the reluctance offered by each substance. The total reluctance then, being the sum of the separate reluctance of each substance. Before the reluctance of any substance included in the magnetic circuit can be calculated, it is necessary to know the permeability of the substance. The permeability depends upon not only the kind and quality of the substance, but also upon the density B of the lines of force. The total induction (magnetic flux N) and the dimensions of the magnet having been determined, the value of $B = N \div A$ for each substance. From a table giving the value of B and H for different magnetic substances the permeability may be calculated by the ratio $B \div H$, or the permeability may be taken directly from Table XIII, page 197.

Having determined the permeability for each substance, the reluctance of each substance can be calculated, and then the total reluctance. The total reluctance of the entire magnetic circuit having been determined, and the total number of lines of force or *magnetic flux* having been established in the beginning by the requirements of the magnet, it becomes necessary to determine the ampere-turns required to drive the magnetic flux around the magnetic circuit.

Since *magnetic flux* $= \frac{\text{M. M. F.}}{R}$, M. M. F. would equal N $\times$ R, and as M. M. F. = ampere-turns $\times$ 3.2, then the ampere-turns required to drive a given magnetic flux through a magnetic circuit would equal

$$\text{Ampere-Turns} = \frac{N}{3.2} \times \text{total R.}$$

Prob. 71: Fig. 185 represents an annealed wrought iron horseshoe core and keeper, separated by an air gap of one quarter of an inch; the dotted line represents the total length of the magnetic circuit. Find the reluctance of each part of the magnetic circuit and the ampere-turns required to drive 50,000 lines of force through the magnetic circuit.

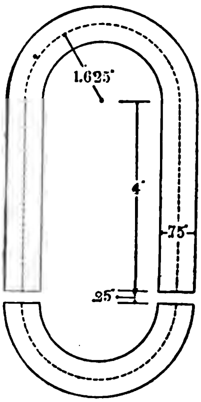


Fig. 185.—The Dotted Centre Line Represents the Mean Length of the Magnetic Circuit.

SOLUTION: Before the reluctance of the horseshoe core can be determined it is necessary to ascertain its complete length, area and permeability:

Length of both limbs of core up to curved portion $= 4.25'' \times 2 = 8.5$ inches; curved portion of core, radius $= 1.625''$,

Circumference of a circle = diam. $\times$ 3.1416, or radius $\times 2 \times 3.1416$,

One-half the circum. = radius $\times$ 3.1416 = $1.625'' \times 3.1416 = 5.105$ inches length of curved portion of core;

Then,

$8.5 + 5.105 = 13.605''$ total length of core.

Area $= d^2 \times .7854 = .75'' \times .75'' \times .7854 = .441$ sq. in.

Induction per sq. in. $= B = \frac{N}{A} = \frac{50{,}000}{.441} =$ 113,378 lines of force.

From Table, VIII μ would equal the mean μ for wrought iron at 110,000 and 115,000, or $180 + 120 \div 2 = 150$ μ for 113,378.

Then,

$$\text{Reluctance of core } R = \frac{l}{A \times \mu} = \frac{13.605}{.441 \times 150} = .205$$

Reluctance of air gaps,
Total length of gaps = .5 inch (each gap .25"),
Area same as core,
μ for air = 1.

$$R = \frac{l}{A \times \mu} = \frac{.5}{.441 \times 1} = 1.133 \text{ R of both gaps.}$$

Reluctance of keeper:

Keeper is bent to the same radius as upper part of horseshoe, therefore its length is the same; area is the same, therefore value of B and permeability is the same, since it is of the same material.

$$R = \frac{l}{A \times \mu} = \frac{5.105}{.441 \times 150} = .077 \text{ R of keeper.}$$

$$\text{Total } R = .205 + 1.133 + .077 = 1.415.$$

Then,

$$\text{Ampere-Turns } \frac{N}{3.2} \times \text{total } R = \frac{50{,}000}{3.2} \times 1.415 = 22{,}109.37$$

ampere-turns.

Table XIII.—Permeability Table.*

Density of Magnetisation.		Permeability.			
Lines per square inch.	Lines per square centimeter.	Annealed Wrought Iron.	Commercial Wrought Iron.	Gray Cast Iron.	Ordinary Cast Iron.
20,000	3,100	2,600	1,800	850	650
25,000	3,875	2,900	2,000	800	700
30,000	4,650	3,000	2,100	600	770
35,000	5,425	2,950	2,150	400	800
40,000	6,200	2,900	2,180	250	770
45,000	6,975	2,800	2,100	140	730
50,000	7,750	2,650	2,050	110	700
55,000	8,525	2,500	1,980	90	600
60,000	9,300	2,300	1,850	70	500
65,000	10,100	2,100	1,700	50	450
70,000	10,850	1,800	1,550	35	350
75,000	11.650	1,500	1,400	25	250
80,000	12,400	1,200	1,250	20	200
85,000	13.200	1,000	1,100	15	150
90,000	14,000	800	900	12	100
95,000	14,750	530	680	10	70
100,000	15,500	360	500	9	50
105,000	16,300	260	360		
110,000	17,400	180	260		
115,000	17,800	120	190		
120,000	18,600	80	150		
125,000	19,400	50	120		
130,000	20,150	30	100		
135,000	20,900	20	85		
140,000	21,700	15	75		

*Weiner's Dynamo Electric Machines.

199. Coarse and Fine Wire Electromagnets.—The same results may be accomplished by the use of magnets wound with coarse wire or fine wire; each type has its advantage according to the manner in which it is to be used. The magnets of an electric bell, telephone, or telegraph instrument are wound with fine wire, as they are usually located at some distance from the battery, so that the current may be very small, and the line small in area, the magnetising force being produced by a small current and thousands of turns. When it is desired to operate a magnet from a 110-volt circuit it is wound with fine wire, so that its resistance will be high, requiring a small current, and thus making it inexpensive to operate. The same magnetic pull could be obtained with a coarse wire magnet in the latter case, by the use of a large current, at an increase in the coast of operation.

Electromagnets operated in series, as in arc lamps, circuit breakers, etc., are wound with coarse wire, having a low resistance, since the whole current passes through the

coil, the magnetising force being produced by a large current and few turns.

200. Testing the Attractive Force of an Electromagnet.—The magnetism of an electromagnet increases as the current through it is increased, up to the saturation point (see ¶ 29), but is not directly proportional to the current; that is, if one ampere, through a certain magnet requires a force of 56 pounds to detach its keeper when 2 amperes are passed through it, twice the force, or 112 pounds, is not required, but usually much less. To make a test of the effect of different current strengths upon the attractive power, the magnet and keeper may be arranged in connection with a spring balance and windlass, as shown in Fig. 186. When the crank is turned the pounds pull may be noted till the detachment of the keeper takes place.

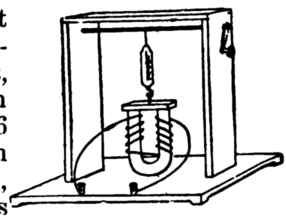


Fig. 186.—Testing the Attractive Force of an Electromagnet.

201. Magnetisation Curve.—Unlike the constant resistance offered by a piece of copper to different strengths of an electric current, the reluctance of a piece of iron varies with each density of the lines of force accommodated through it, and this variation bears no constant ratio to the number of lines of force passing through it. For this reason *curves of magnetisation* are constructed for different specimens of iron, showing the relation of the induction to the magnetising force at different stages of magnetisation. Fig. 187 shows magnetisation curves of steel and iron, the curves gradually sloping upwards with each increased exciting current until the saturation point is reached, when the curve slopes off to the horizontal.

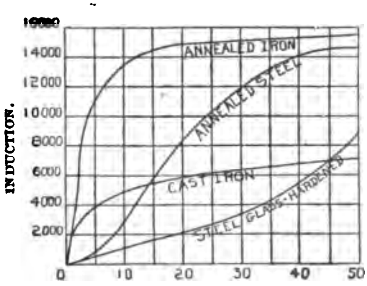


Fig. 187.—Magnetisation Curves of Steel and Iron.

With a given magnetising force in ampere-turns the relative induction may be found from the curves.

202. Tractive Force of an Electromagnet.—The lifting or adhesive power of an electromagnet is called its *tractive force*, or simply, *traction*. The tractive force is proportional to the square of the density of lines of force per square inch (B), and the area of the surface contact. To determine the tractive force, or "pull" in pounds of an electromagnet, let B = density, number of lines of force per square inch; A = area of contact in square inches; P = pull in pounds.

$$\text{Then,} \qquad P = \frac{B^2 \times A}{72,134,000}$$

For example: suppose a density of 45,000 lines of force per square inch is produced in an electromagnet by the magnetising force. What would be the pounds pull required to detach keeper if the poles of magnet had a total area of 1 square inch?

$B^2 = 45,000^2 = 2,025,000,000$; $A = 1$ sq. in.;
Pull (in pounds) $= 2,025,000,000 \times 1 \div 72,134,000 = 28$ pounds.

Due to *magnetic leakage*, that is, some of the magnetic lines leaking away from the attracting surface, the actual pull will be less than the calculated pull.

QUESTIONS.

1. The pole of an electromagnet having a soft steel core deflects a compass needle 44 degrees when held at a distance of one foot. A soft iron core is substituted for the steel and the deflection is now 58 degrees. How do you account for this, since neither the distance nor the current strength is altered?
2. Define magnetic permeability.
3. Which magnet core mentioned in question 1 possesses the greater permeability?
4. Wind a steel key ring with insulated wire so that when a current is sent through the windings the ring will possess two diametrically opposite poles. Illustrate by sketches the direction of winding, direction of current, and direction of the magnetic lines of force.
5. What kind of poles are produced in the key ring in question 4?
6. What is reluctance?
7. How does the magnetic reluctance of air compare with that of iron?
8. An electromagnet connected in series with some incandescent lamps connected in parallel, increases the resistance of the circuit abnormally though it possesses the proper number of pounds pull. What change in connections and construction would you suggest so that the magnet would still possess the same lifting power and the lamps burn at their proper candle power?
9. The magnetomotive force of a solenoid is doubled. How would this affect the number of lines of force threading through it?
10. What is your answer to question 9 when the solenoid possesses a brass core? A soft iron core?

LESSON XVIII.

AMMETERS.

Measurement of Current Strength, Ampere-Meters—Gravity Ammeter—Connecting Ammeters in Circuit—Balance Beam Ammeter—Thomson Inclined Coil Ammeter—Weston Ammeter—Weston Ammeter Shunt—Questions.

203. Measurement of Current Strength, Ampere Meters.—An *ammeter* which is the commercial name for ampere meter, is a galvanometer designed to show by direct reading the number of amperes of current flowing through any circuit in which it may be inserted. The voltameters and tangent galvanometer previously described for measuring current strength are used in the laboratory for standardizing commercial direct-reading instruments, required for portable use or upon station switchboards. A great variety of ammeters have been invented, based upon the principles given in ¶ 180. A good ammeter should have a *very low resistance*, so that very little of the energy of the circuit in which it is inserted will be absorbed by it: the needle should be *dead beat*, ¶ 189, and so sensitive as to respond to minute variations of current; the scale divisions not cramped at either end of the scale, but even throughout; and the accuracy of the instrument should not be impaired when in close proximity to powerful magnetic fields, as switchboard conductors or dynamos. Ammeters are divided according to their use, into two classes: (1) a *portable type*, generally of a high class of construction and accuracy, used for measurements of precision, and (2) the *switchboard type*, in the construction of which such refinement of precision is not required. In some makes of both types the *whole current* passes through the ammeter, while in others the ammeter is *shunted*, ¶ 209. The shunt may either be contained within the instrument case, or it may be external to the instrument. In the latter case special leads used in the calibration are furnished to connect the shunt with its instrument. *Milliammeters* are ammeters in which the scale is graduated to read directly in thousandths of an ampere.

204. Gravity Ammeter.—In this simple type of ammeter, the magnetising current overcomes the attraction of gravity for a piece of suspended iron. The current passes around a helix of *heavy wire*, which is bent in the arc of a circle, Fig. 188. A soft iron core bent to the same arc is suspended, so that one end is free to be sucked up into the helix by the field of the magnetising current. A pointer attached to the movable iron core swings over the scale, and will assume a different position for each value of the magnetising current.

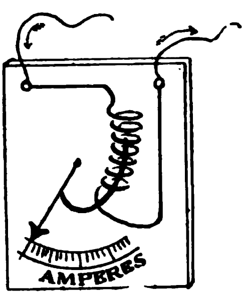


Fig. 188.—Solenoid Gravity Ammeter.

The instrument is calibrated by inserting it in series with a laboratory standard and marking the value of each current passed through it on the scale corresponding to each position of the pointer. Suppose that when 10 amperes were sent through the helix the core was in such a position as to accommodate through itself the greatest number of the magnetic lines of the helix, then the limit of the scale was attained and the capacity of the instrument was 0 to 10 amperes. By attaching a small weight to the core, if the wire were of sufficient size to carry the current, the capacity could readily be made 0 to 20 amperes. The division per ampere would, however, be about one-half as large. The objection to this type of instrument is that the movement of the core is much greater at some positions than at others for the same increment of current, giving a scale of unequal divisions, and generally cramped at each end. The instrument is not dead beat, is readily affected by magnetic fields, and can only be used in a vertical position.

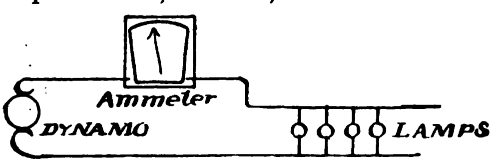


Fig. 189.—Ammeter *Correctly* Connected in Series with the Circuit.

205. Connecting Ammeters in Circuit.—Since the total current to be measured in any circuit must flow through an ammeter, an *ammeter must always be connected in series with the circuit* and between the generator and apparatus receiving the current, as in Fig. 189. Suppose the coil in a gravity

ammeter has a resistance of .1 ohm and that it is *incorrectly* placed in parallel with some incandescent lamps connected to a dynamo, Fig. 190. How much current will flow through the ammeter if the pressure is 110 volts between the mains? The current that would flow through the ammeter would be by Formula (28) $I = \frac{E}{R} = \frac{110}{.1} =$ 1100 amperes or enough to *totally destroy the instrument* by excessive heating, since the current-carrying capacity of the wire would be far below this value. ¶ 257.

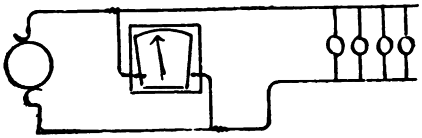


Fig. 190.—Ammeter *Incorrectly* Connected in Parallel with the Circuit.

206. Balance Beam Ammeter.—In the form of ammeter, illustrated in Fig. 191, a horizontal beam is supported on a knife bearing. An iron core made up of a bundle of soft iron wires is suspended by a hook from one end of the beam and is balanced by a counterweight on the other end. The current to be measured is passed through a coil of a few turns of heavy wire located directly below the core, and attracts it, to a certain distance, for each value of the current sent through the coil. A pointer attached to the beam swings over the scale, which is calibrated to read in amperes. A plumb-bob indicates when the instrument is properly leveled. The instrument depicted illustrates a 0 to 300 scale, and can be calibrated for a larger capacity, say 0 to 400 amperes, by sliding the counterweight along the beam toward the right, when a greater magnetic pull than before would be required for each position of the core. A 150 ampere instrument, of this type, contains 6 turns of No. 0 B. & S. copper wire, the resist-

Fig. 191.—Balance Beam Gravity Ammeter—Westinghouse Type.

ance of the instrument being about .0001 ohm. The instrument may be calibrated for an alternating or direct current circuit.

207. Thomson Inclined Coil Ammeter.—In many types of ammeters, beside the above, the magnetic body is a piece of iron, rather than a magnet, and placed so that it will gradually move to accommodate through itself the lines of force of the magnetising coil. The Thomson inclined coil ammeter utilizes this principle and is constructed in the portable and switchboard patterns. A view of the portable type, with cover removed, is shown in Fig. 192, and a sectional view in Fig. 193. A circular coil of wire, C, is mounted with its axis inclined to the horizontal. Through the centre of the coil is passed a vertical shaft mounted between jewel centres and carrying a pointer at its upper end. A small iron vane, A, is attached to the shaft at an angle, and the movable system is controlled by the two flat springs, S.

Fig. 192.—Thomson Inclined Coil Ammeter.

When current is passed through the coil the vane tends to turn against the action of the springs, so as to become parallel to the lines of force indicated by the direction of the arrows. The turning of the shaft causes the pointer, P, to sweep over the scale. The coils for large sizes of instruments are generally wound with a few turns of flat insulated copper ribbon having a very low resistance. These meters are adapted for use with alternating or direct currents.

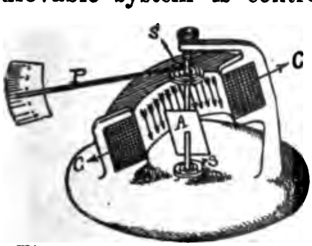


Fig. 193.—Construction of Inclined Coil Ammeter.

208. Weston Ammeter.—The construction of this instrument is based upon the principle of the D'Arsonval galvanometer, ¶ 191. A general view of a portable instrument is

shown in Fig. 194, and interior views in Figs. 195 and 196. A permanent horseshoe magnet, M, is fitted with soft iron pole pieces, P P, Fig. 197, between which a stationary cylinder of soft iron, C, is supported by a brass piece extending across the pole pieces. The iron cylinder is smaller in diameter than the bore of the pole pieces, so that the magnetic lines of force pass across this air gap, making a very strong and uniform magnetic field. The movable system is shown in Fig. 198. It consists of a rectangular coil of wire, wound upon a bobbin of thin sheet copper or aluminum and delicately suspended between jewel bearings. The terminals of the coil are connected to the horizontal spiral springs, against which the coil acts when it tends to rotate, the springs serving to also conduct the current to and from the coil. A thin aluminum knife-edge pointer attached to the bobbin and swinging over the scale, Fig. 195, indicates the angle of deflection of the coil. This coil is mounted concentrically with the iron cylinder and pole pieces in the air gap, as shown in Fig. 196, where part of the pole piece,

Fig. 194.—Weston Ammeter with Self-Contained Shunt.

Fig. 195.—Weston Ammeter with Cover Removed Showing D'Arsonval Galvanometer.

etc., have been cut away. When a current is sent through it, by the springs, the coil tends to move through the magnetic field, to take up a position so that its lines of force will be in the same direction as those of the field. It will so move until the torsion of the springs is balanced by the force tending to move the coil, when the pointer will indicate the angle of deflection. The angle of deflection is nearly proportional to the current throughout the movement, which gives a very uniform scale, as can be seen from Fig. 195. The metallic bobbin on which the coil is

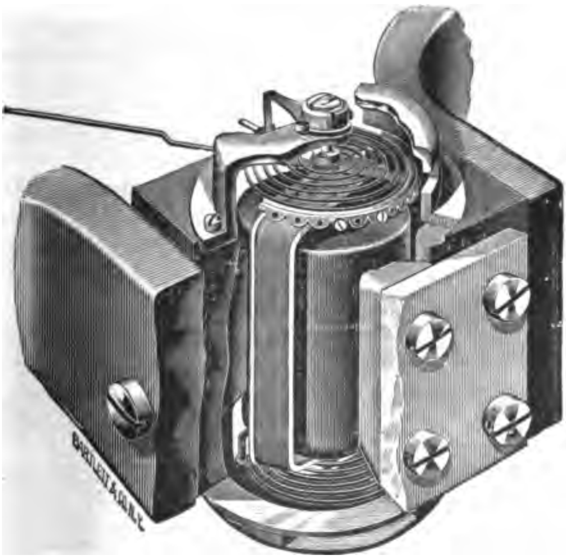


Fig. 196.—Method of Mounting the Movable Coil in Weston Instruments.

wound has an electromotive force induced in it, only while the coil is moving, which causes eddy currents, ¶ 292, to flow around the bobbin in the opposite direction to the current in the coil. These momentary currents tend to stop the motion of the coil, and have the effect of preventing the needle from oscillating, thus bringing it to rest quickly at the proper position and making the instrument very dead-beat, ¶ 189. The movable coil is extremely light, the friction small, and the instrument very sensitive to minute variations

of current. A current of about .015 ampere will give a full scale deflection of the pointer. The instrument is carefully balanced, so that it may be used in a horizontal or vertical position. An ammeter, however, should always be calibrated in the position in which it is to be used. A mirror is located just below the scale of the portable instruments. By looking down on the pointer so that it is directly over its reflection in the mirror, errors in reading the scale divisions due to *parallax** are thus avoided. In Weston instruments the post marked + is the one by which the current should enter the instrument so that the coil will be deflected in the right direction.

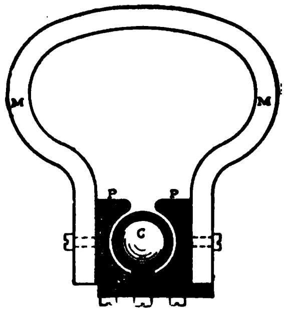


Fig. 197.—The Magnetic Circuit of the Weston Instruments.

209. Weston Ammeter Shunt.—Only a small portion of the total current to be measured is sent through the movable coil, the remainder passing through a shunt, ¶ 162. The shunt is made of a special resistance alloy, and contained either in the instrument, in a separate portable case, or on an external block, Fig. 199, as in the switchboard type of instruments. The lead wires to the shunt, the instrument and the shunt, are all numbered to correspond, so that when used together the indications agree with the calibration. The shunt leads should never be shortened, because the decreased resistance in the shunt circuit would permit more current to flow through it, so that the indicated readings would be higher than the actual current flowing. The resistance of the

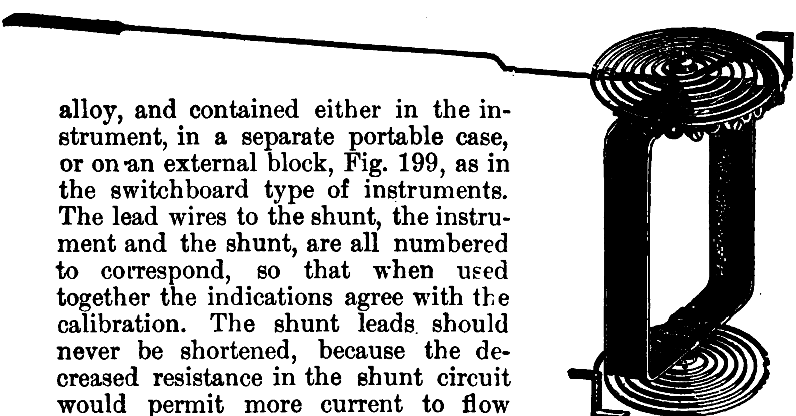


Fig. 198.—The Movable Coil, Springs and Pointer of Weston Instruments.

*The apparent angular displacement of an object when seen from two different points of view.

instrument and its shunt is very low, little energy, therefore, being lost when it remains continually in circuit. A 15 ampere shunted instrument has a joint resistance of .0022 ohm. A number of shunts are sometimes furnished in a separate case for a single portable instrument, which is called a *multiplier*, and is used for increasing the range or capacity of the instrument. For example, with a shunt of .004 ohm in Fig. 199, suppose the coil receives sufficient current to deflect the pointer entirely across the scale, and this deflection corresponds to 50 amperes in the main circuit. The difference in pressure between the shunt terminals by Ohm's Law is equal to $I \times R = 50 \times .004 = 0.2$ volt. Now the shunt is reduced in resistance to one-half .004 or .002 ohm, and the pressure applied to the movable coil for the same current is equal to $I \times R = 50 \times .002 = .1$ volt, or the coil will receive only one-half the former current, and thus be deflected to the middle of the scale. The range of the ammeter is now 0 to 100 amperes, or each scale reading must be multiplied by 2 to obtain the true value of the current when used with this shunt. In the same manner with a reduction of the shunt's resistance to one-third of its original value, the range is increased three-fold and the readings are multiplied by 3. One advantage of an external shunt in switchboard instruments for power stations is, that instead of running heavy copper cables to a distant ammeter, a shunt may be inserted in the cable circuit and the two small size shunt leads wired to the instrument, thus effecting an economy in copper and construction. A *Weston ammeter* may be used without its shunt as a *millivoltmeter*, in which case it is quite sensitive and adapted to many electrical measurements. When resistance is added in series with it, it becomes a long coil galvanometer, and may be calibrated as a direct reading voltmeter, ¶ 180. The same mechanical construction is employed in Weston voltmeters, ¶¶ 234 and 235, the only difference being in the value of the extra resistance added and the method of connecting it to the instrument.

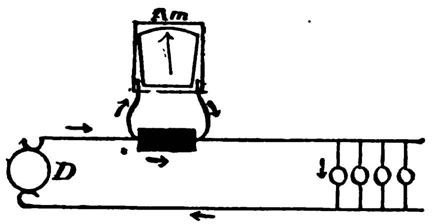


Fig. 199.—Connections of an Ammeter with a Portable Shunt.

To measure currents larger than the capacity of an ammeter.

Let $\mathbf{R}$ = resistance of shunt required;
$\mathbf{r}$ = resistance of ammeter;
$\mathbf{A}$ = range of ammeter;
$\mathbf{A_1}$ = desired range of ammeter.

$$\text{Then, } \mathbf{R} = \frac{\mathbf{A}}{\mathbf{A_1} - \mathbf{A}} \times \mathbf{r} \qquad (57).$$

The indicated readings obtained must be multiplied by $\frac{A_1}{A}$ to be correct.

Prob. 71-A: (1) What will be the resistance of a shunt required to increase the capacity of an ammeter from 150 to 600 amperes? Resistance of the instrument .009. (2) What will be the multiplying power of the shunt?

By Formula (57) $R = \frac{A}{A_1 - A} \times r = \frac{150}{600 - 150} \times .009 = .003$ ohm.

Multiplying power of the shunt $= \frac{A_1}{A} = \frac{600}{150} = 4$, or by Formula (48)

$n = \frac{G}{S} + 1 = \frac{.009}{.003} + 1 = 4.$

QUESTIONS.

1. What is the advantage of a Weston type of ammeter over one constructed to actuate upon the solenoid and core principle?
2. In what respect does the Thomson inclined coil ammeter differ from the Westinghouse balance beam type?
3. An ammeter of 200 amperes capacity is required to be located 50 feet from the main generator cables. What economy would be attained by using a shunt type of instrument in this case?
4. In a station shunt type ammeter a pair of shunt leads are used which are the same length as those furnished with the instrument, but of a smaller size. How will this affect the meter's indications?
5. An ammeter with its leads has a resistance of 50 ohms, and the shunt, a resistance of 0.1 ohm. If 20 amperes are flowing through the shunt what current does the ammeter receive? *Ans.* 0.04 ampere.
6. In question 5, if 20 amperes are flowing through the circuit to which the shunted ammeter is connected, what current flows through the ammeter? *Ans.* 0.0399 ampere.
7. A solenoid ammeter having a resistance of 0.5 ohm is incorrectly connected in parallel with 10 incandescent lamps in parallel. Each lamp has a resistance of 220 ohms and requires 0.5 ampere. What current will flow through the ammeter when the circuit is closed? *Ans.* 220 amperes.
8. It is desired to use a solenoid ammeter of only 50 amperes capacity in a circuit through which 150 amperes are flowing. How would you do this?
9. How much resistance would you add if the instrument in question 8 had a resistance of .06 ohm? Make a sketch. *Ans.* 0.03 ohm.
10. By what should the indications of the ammeter in question 9 be multiplied in order to obtain the true reading? *Ans.* 3.

LESSON XIX.

ELECTRICAL WORK AND POWER.

Force—Different Kinds of Force—Mass and Weight—Work—Power—Horse Power of a Steam Engine—Difference Between Energy, Force, Work, and Power—Electrical Work—Electrical Power—Heat and Work—Equivalents of Mechanical and Electrical Work—Electrical Horse Power—The Kilowatt—The Watt-Hour and Kilowatt-Hour—Electrical Power Calculations—Electrical Power Formulæ—Power from Cells—Efficiency of a Battery—Questions and Problems.

210. Force.—Force is defined as that which produces motion, or a change of motion or matter; thus force must always be applied to any body to cause it to move. To increase, decrease, or stop this motion, that is to change it, force must again be applied. For example, to start a loaded wheelbarrow force must be applied, either by pushing or pulling it, but when it is set in motion less force will be required to keep it in motion; to cause a change in motion, that is to increase or decrease the speed, extra force must be applied. Force does not always produce motion, but only tends to produce it, as when a man tries to push a laden freight car he applies all his muscular force, but no motion results.

211. Different Kinds of Force.—There is the *force of gravitation*, in virtue of which all bodies free to move will fall from a higher to a lower level. The force exerted by a man riding a bicycle or a horse drawing a carriage are examples of *muscular force.* An engine draws a train of cars by reason of the *mechanical force* applied, which is due to the expansion of the steam in the steam cylinder. A mixture of air and illuminating gas in a room is ignited and the explosion wrecks the room; the action is due to the *chemical force* exerted. The force which produces or tends to produce a flow of electricity is *electromotive force.* The force which sets up magnetic lines of force is *magnetomotive force.* The rate at which a train moves depends upon the force exerted by the engine, so also, the rate of flow of electricity depends upon the amount of electromotive force applied.

212. Mass and Weight.—The *mass* of a body is the quantity of matter in it; the *weight* of a body is due to the force of gravity acting upon this matter. Since the force of gravity diminishes as we ascend from the earth's surface, the attraction for a mass of matter will diminish, or it will weigh less on the top of a high mountain than at the sea level; the mass of matter, however, would be the same in each case. Weight is not, therefore, the same thing as mass, but we can conveniently measure a body by its weight.

213. Work.—Work is done when force overcomes a resistance, or, *work is force acting through space* ($W = F \times S$).

$$\text{Work} = \text{Force} \times \text{Distance},$$
$$\text{or Work} = \text{Pounds} \times \text{Feet} = \text{Foot-pounds.}$$

Work is not always done when a force acts; for instance, a man pushes with all his force against a brick wall; he is exerting force, but doing no work because no motion results, nor is any resistance overcome. If a weight be lifted, work is done directly in proportion to the weight and to the distance through which it was moved. Thus, the work done in lifting 4 pounds to a height of 3 feet is equivalent to 12 foot-pounds of work. Exactly the same work is performed when 2 pounds are raised 6 feet; or 6 pounds raised 2 feet; or 12 pounds raised one foot. Work does not always consist in raising weights; the steam engine does work by hauling a train, due to the expansive force of steam acting upon the piston; an explosion of powder in a cannon causes an iron ball to traverse a certain distance. The chemical action in a cell sets up a force which causes a current to flow through an electric motor and the motor drives an automobile weighing so many pounds a certain number of feet every minute, hence the total foot-pounds of work are performed electrically. The work in each case is measured in foot-pounds. Whether work be done mechanically, chemically, thermally, or electrically, it can be expressed in foot-pounds. The total amount of work done is independent of time, that is, the same work may be performed in one hour or one year. When different amounts of work performed in different times are to be compared, then reference is made to the time, or rate of working, or the power.

214. Power.—Power is the rate at which work is done, and is independent of the amount of work to be done.

Power (rate of working) $= \frac{\text{Work}}{\text{Time}} = \frac{\text{Foot-pounds}}{\text{Time}} =$ Foot-pounds per unit of time.

For example, it requires four hours for a particular engine to draw a train from one station to another, while another engine may draw the same train the same distance in two hours. One engine is thus twice as powerful as the other, because it can do the same work in one-half the time. When the train had reached its destination it would have represented the same amount of work done, no matter whether it had traveled at one mile per minute or one mile per hour, leaving, of course, friction and air resistance out of account.

Power is estimated according to the amount of work done in a given period of time. As mechanical work is measured in foot-pounds, mechanical power would thus be so many foot-pounds per minute, or per second. The mechanical unit of power is the horse power.

ONE MECHANICAL HORSE POWER = 33000 FT. LBS. PER MINUTE, or

$$\frac{33000}{60} = 550 \text{ ft. lbs. per second.}$$

If a body weighing 33000 pounds be raised one foot every minute then we have a rate of working equal to one horse power; or if 16500 pounds be raised two feet per minute, the rate of working is the same, one horse power. If the work were continued at the same rate for one hour, we would have a larger unit of work, or the *horse-power-hour*. When we say that an engine is developing 40 horse power we mean that it is performing $550 \times 40 = 22000$ foot-pounds of work every second.

215. Horse Power of a Steam Engine.—The horse power of a steam engine may be readily calculated from data obtained from it while it is working. The mean pressure of the steam upon the piston is found by attaching a graphical recording indicator to the steam cylinder which shows the various steam pressures during a stroke of the piston. From this "card," as it is termed, the average or mean effective pressure throughout the stroke is obtained. The speed of the engine must be noted while the card is taken but the length of stroke in feet, and area of the piston-head in square inches should be previously obtained.

The following formula may then be used to ascertain the rate of working, or horse power developed corresponding to the above conditions :

$$\text{Horse power of a steam engine} = \frac{P \times L \times A \times N}{33000} \quad . \quad . \ (58).$$

When P = mean effective steam pressure in pounds (from indicator card);

L = length of stroke in feet;

A = area of piston-head (in square inches);

N = number of strokes per minute (twice the number of revolutions).

Prob. 72: From an indicator card the mean steam pressure is 45 lbs., the speed of the engine 275 revolutions, length of stroke 12 inches, area of piston-head one-half a square foot. What horse power is developed by the engine?

By Formula (58) $\text{H. P.} = \frac{P \times L \times A \times N}{33000} = \frac{45 \times 1 \times 72 \times 550}{33000}$ = 54 H. P.

$P = 45$ lbs., $L = 12$ inches $= 1$ foot, $A = \frac{1}{2}$ sq. ft. $= 72$ sq. in.
$N = 275$ revolutions $\times$ 2 strokes per rev. $= 550$.

216. Difference Between Energy, Force, Work, and Power.—It is important that the student should thoroughly understand the meaning of the above terms. *Energy* is the capacity to do work. *Force* is one of the factors of work and has to be exerted through a distance to do work, the work being reckoned as the product of the force and the distance through which it has been applied. *Work* is done when energy is expended or when force overcomes a resistance. *Power* is the rate of working.

217. Electrical Work.—Work is force acting through space, or energy expended, therefore, resistance is overcome when work is performed. Force may exist without work being performed, as when you push against a table and do not move it, no work is done, yet the force exists. An electrical force exists between the two terminals of a battery, tending to send a current of electricity from one to the other through the air. The force is not sufficient to overcome the resistance, of the air, therefore no current flows and the battery is not doing any work; the same is true with a dynamo when running on open circuit. When a wire is connected across the battery terminals, the force overcomes the resistance of the wire and electricity is moved along, around or through the wire, which becomes heated. The electrical work, or

energy expended, is represented by the amount of heat generated in this instance, ¶ 257. With a small lamp connected to the battery, the work is represented by the heat and light given by the lamp as well as the heat given to the remainder of the circuit. The total work performed is the product of the force, the current, and the time that the current is maintained, or

Electrical Work = Volts × Amperes × Time.

The unit of electrical work is the amount of work performed by a current of one ampere flowing for one second under a pressure of one volt and is called a joule.

Since an ampere flowing for one second is equal to one coulomb, ¶ 116, a joule is, therefore, one volt-coulomb and is analogous to the mechanical unit of work, the foot-pound, which has no special name. The volt-coulomb is not so great as the foot-pound, however,

$$1 \text{ joule} = .7375 \text{ foot-pound};$$
$$1 \text{ foot-pound} \doteq 1.356 \text{ joules}.$$

Larger units of electrical work are given in ¶ 221.

TO FIND THE TOTAL ELECTRICAL WORK, IN JOULES, PERFORMED IN ANY CIRCUIT :

Multiply the volts causing the current to flow by the current and the time it flows, expressed in seconds.

$$\text{Joules} = \text{volts} \times \text{amperes} \times \text{seconds},$$
$$\text{or } J = E \times I \times t \quad \ldots\ldots\ldots\ldots \quad (59).$$

When t = the time in seconds;
J = work in joules.

Prob. 73: A current of 20 amperes is maintained through a number of incandescent lamps for one hour by a pressure of 110 volts. How much electrical work has been performed?

By Formula (59) $J = E \times I \times t = 110 \times 20 \times 3600 = 7920000$ joules.
$E = 110$ volts, $I = 20$ amperes, $t = 60 \times 60 = 3600$ seconds.

TO FIND THE TOTAL ELECTRICAL WORK, IN JOULES, PERFORMED IN ANY PART OF THE CIRCUIT WHEN THE CURRENT STRENGTH AND RESISTANCE ARE KNOWN :

Multiply the square of the current by the resistance, and this product by the time the current flows.

$$J = I \times I \times R \times t,$$
$$\text{or } J = I^2 \times R \times t \quad \ldots\ldots\ldots \quad (60).$$

By substituting for E in Formula (59) its value $I \times R$, we get Formula (60). Also by substituting the value of I, which equals $E \div R$ in Formula (59), we obtain an expression to find work in joules when the volts and resistance are known.

By Formula (59) $J = E \times I \times t$.

$$\text{Substituting, } I = \frac{E}{R} \text{ then } J = \frac{E \times E}{R} \times t,$$

$$\text{or } J = \frac{E^2}{R} \times t \quad . \; . \; . \; . \; . \; . \; . \; . \quad (61).$$

Prob. 74: A current of 5 amperes is passed for one-half hour through an arc lamp, the resistance of which is 4 ohms, hot. How much energy has been expended?

By Formula (60) $J = I^2 \times R \times t = 5 \times 5 \times 4 \times 1800 = 180000$ joules. $I = 5$ amperes, $R = 4$ ohms, $t = \frac{1}{2}$ hour $= 1800$ seconds.

Prob. 75: The resistance of the copper cables connecting a dynamo with its switchboard is .1 ohm, and 2 volts are required to send the full load current through them. How much energy is expended in 10 hours?

By Formula (61) $J = \frac{E^2}{R} \times t = \frac{2 \times 2}{.1} \times 36000 = 1440000$ joules.

$E = 2$ volts, $R = .1$ ohm, $t = 60 \times 60 \times 10 = 36000$ seconds.

218. Electrical Power.—Power is the rate at which energy is expended, and is independent of the total work to be accomplished. The rate of working, or the power is found by dividing the total work by the time required to perform it.

$$\textbf{Electrical Power} = \frac{\textbf{Electrical Work}}{\textbf{Time}}.$$

The unit of electrical power is a unit of work performed in a unit of time, or a joule per second, and is called a *watt.* Therefore:

$$\text{Watts} = \frac{\text{work}}{\text{time}} = \frac{\text{joules}}{\text{seconds}} = \frac{\text{volts} \times \text{amperes} \times \text{seconds}}{\text{seconds}} =$$
volts × amperes.

One watt therefore equals one volt multiplied by one ampere, or 2 volts by .5 ampere, etc.

1. To Find the Rate in Watts at which Energy is Expended in a Circuit:

Multiply the current in amperes by the pressure causing it to flow

Let W = watts expended;
I = current in amperes;
E = pressure in volts.

Then, watts = volts × amperes,

$$\mathbf{W} = \mathbf{E} \times \mathbf{I} \quad \ldots \ldots \ldots \quad \mathbf{(62).}$$

2. To Find the Current when the Watts and Pressure are Known:

Divide the watts expended by the voltage causing the current to flow.

From Formula (62) W = E × I.

Therefore,

$$\text{Amperes} = \frac{\text{Watts}}{\text{Volts}} \text{ or } \mathbf{I} = \frac{\mathbf{W}}{\mathbf{E}} \quad \ldots \ldots \ldots \quad \mathbf{(63).}$$

3. To Find the Pressure when the Watts and Current are Known:

Divide the watts expended by the current flowing.

From Formula (62) W = E × I.

Therefore,

$$\text{Volts} = \frac{\text{Watts}}{\text{Amperes}} \text{ or } \mathbf{E} = \frac{\mathbf{W}}{\mathbf{I}} \quad \ldots \ldots \ldots \quad \mathbf{(64).}$$

Prob. 76: How many watts are consumed by one hundred incandescent lamps connected in multiple to a 110 volt circuit, supposing each lamp to have resistance (hot) of 220 ohms?

$$I = \frac{E}{R} = \frac{110}{220} = \frac{1}{2} \text{ ampere per lamp.}$$

$$W = E \times I = 110 \times \frac{1}{2} = 55 \text{ watts per lamp.} \quad 55 \times 100 = 5500 \text{ watts.}$$

Prob. 77: What current is required to operate a 50-watt lamp on a 100-volt circuit?

By Formula (63) $I = \frac{W}{E} = \frac{50}{100} = \frac{1}{2}$ ampere.

W = 50 watts, E = 100 volts.

Prob. 78: A 500-watt motor requires a current of 10 amperes. What E. M. F. is necessary to operate it?

By Formula (64) $E = \frac{W}{I} = \frac{500}{10} = 50$ volts.

W = 500 watts, I = 10 amperes.

219. Heat and Work.—One of the most important discoveries in science is that of the *equivalents of heat and work*: that is, that a *definite quantity of mechanical work can always produce a definite quantity of heat and, conversely, this heat,*

if the conversion be complete, can perform the original quantity of work.

All kinds of energy (chemical, mechanical, electrical, etc.) are so related to each other that energy of any kind can be changed into energy of any other kind. This statement is known as the doctrine of *correlation of energy.* When one form of energy disappears an exact equivalent of another form takes its place, so that the sum total of the energy is not changed. This is known as the doctrine of *conservation of energy.* These two principles constitute the corner-stone of physical science.

220. Equivalents of Mechanical and Electrical Work. Dr. Joule, of England, was the first to ascertain the relation existing between mechanical work, heat, and electricity.

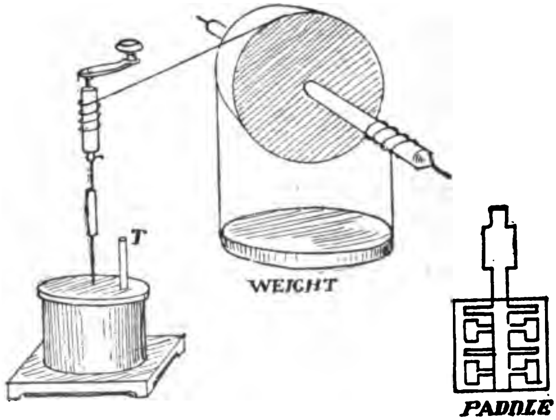


Fig. 200.—Dr. Joule's Paddle Wheel Experiment.

In an experiment he caused a paddle-wheel to revolve in a vessel filled with water, by means of a falling weight attached to a cord and wound around the axle of the wheel, Fig. 200. The resistance offered by the water to the motion of the paddles was the means by which the mechanical motion of the weight was converted into heat, which resistance raised the temperature of the water. From this experiment it was found that 778 foot-pounds of work would raise the temperature of 1 pound of water 1° Fahrenheit:

also by the doctrine, ¶ 219, the heat which would raise 1 pound of water 1° Fahrenheit would also raise 778 pounds 1 foot. The quantity, 778 foot-pounds, is called the *mechanical equivalent of heat*, or Joule's equivalent. If now we heat the pound of water by a current of electricity until its temperature is raised 1° we will have done the same work electrically as was previously done mechanically. An apparatus similar to our calorimeter, ¶ 112, would be suitable for this experiment. The current in amperes and the pressure in volts must be accurately read from instruments.

From this experiment it was found that a current of 1 ampere flowing through the coil for 1 second, under a pressure of 1 volt (or 1 watt expended) would do the same work as .7375 foot-pound expended in 1 second. The rates of working are thus equal since the same work in each case has been accomplished in the same time. Therefore:

One watt = .7375 foot-pounds per second,
or 1 foot-pound = 1.356 watt-second.

Now since 550 foot-pounds per second are equivalent to 1 mechanical horse power, ¶ 214, an equivalent rate of electrical working would, therefore, be:

$$\frac{550}{.7375} = \textbf{746 watts} = \textbf{1 electrical horse power.}$$

A current of 1 ampere and 746 volts, or 1 volt and 746 amperes, etc., maintained through the calorimeter coil for 1 second would heat the water to exactly the same temperature that it would be heated by the paddle wheels when, in 1 second, 550 pounds fall through a distance of 1 foot, or 1 pound falls through 550 feet, etc. If these rates of working are continued for equal periods of time, as an hour, or a day, the water is raised to the same temperature by either method, so that the total work performed is also the same.

221. Electrical Horse Power.—From ¶ 220, the method of obtaining the equivalent of a mechanical horse power in electrical units was given. The watt being a very small unit of power, the larger unit, an *electrical horse power*, is often used.

To Find the Electrical Horse Power (H. P.) Maintained in any Circuit, or Part of a Circuit

Multiply the volts causing the current to flow by the current expressed in amperes and divide this product by 746.

$$\text{H. P.} = \frac{\text{Watts}}{746} = \frac{\text{volts} \times \text{amperes}}{746} = \frac{E \times I}{746},$$

$$\text{or} \quad \text{H. P.} = \frac{E \times I}{746} \quad \ldots\ldots\ldots\ldots \quad \textbf{(65)}.$$

Prob. 79: A dynamo maintains a pressure of 110 volts across an electric light circuit when the ammeter indicates 100 amperes; what horse power is being developed by the machine?

By Formula (65) $\text{H. P.} = \frac{E \times I}{746} = \frac{110 \times 100}{746} = 14.7 \text{ H. P.}$

222. The Kilowatt.—The *kilowatt* (abbreviated K. W.) is a larger unit of electrical power. *One kilowatt equals 1000 watts*, or is about $1\frac{1}{3}$ times as large as the horse power unit.

$$\text{Kilowatts (K. W.)} = \frac{\text{Watts}}{1000} = \frac{E \times I}{1000} \quad \ldots \quad \textbf{(66)}.$$

$$\text{Watts} = \text{K. W.} \times 1000 \quad \ldots\ldots\ldots\ldots \quad \textbf{(67)}.$$

$$1 \text{ H. P.} = 0.746 \text{ K. W.}$$

$$1 \text{ K.W.} = 1.34 \text{ H. P.}$$

Prob. 80: What is the capacity in kilowatts of a generator carrying a load of 120 volts and 500 amperes?

By Formula (66) $\text{K. W.} = \frac{E \times I}{1000} = \frac{120 \times 500}{1000} = 60 \text{ K. W.}$

Prob. 81: How many amperes will be maintained by a 40 K. W. dynamo at a pressure of 100 volts?

By Formula (67) Watts $=$ K.W. $\times$ 1000 $= 40 \times 1000 = 40000$ watts.

By Formula (63) $I = \frac{W}{E} = \frac{40000}{100} = 400$ amperes.

223. The Watt-Hour and Kilowatt-Hour.—The joule is a very small unit of electrical energy or work, so that larger units are generally used in practice. A *watt-hour* is one watt exerted or expended for one hour. It is equivalent to 3600 watt-seconds or 60 watt-minutes.

Watt-hours = watts × hours.

The dials of consumer's meters, used to measure the electrical energy supplied for lighting and power, generally record watt-hours, ¶ 275. A *kilowatt-hour* is a larger unit of electrical work and is equal to 1000 watts or 1 K. W. expended in one hour, or 500 watts expended in two hours, etc.

KILOWATT-HOURS = K. W. × HOURS.

An electrical *horse-power-hour* is one electrical horse power maintained for one hour, or 746 watts maintained for one hour.

Horse-power-hours = H. P. $\times$ hours.

Electrical energy is generally supplied from stations at a fixed rate per horse-power-hour or kilowatt-hour. The total cost of producing a kilowatt-hour varies with many station conditions; from about 2 to 7 cents per kilowatt-hour is the range in a number of plants.

224. Electrical Power Calculations.—The following rules and formulæ have been derived either by transposing the formulæ in ¶¶ 220 to 224, or by combining them with the formulæ given in Lesson XIII, Ohm's Law. This lesson is practically a continuation of Ohm's Law and is very important, as by it many practical electrical problems are solved. The formulæ apply equally well to the whole or any part of a circuit; as, for example, to the lead wires to a lamp, as well as to the lamp itself, or the internal resistance of a battery or dynamo. *Caution must be exercised to use the volts lost or drop, ¶ 230, in the particular part of any circuit considered, also the resistance of, and the current through this part only.* The symbols used to represent the quantities are as given heretofore, and are again enumerated as follows:

E = pressure, E. M. F. or difference of potential, causing the current to flow, expressed in volts;
R = resistance of the circuit or part of the circuit expressed in ohms;
I = current in amperes;
W = watts expended or lost in the resistance;
H. P. = electrical horse power (746 watts);
K. W. = kilowatt (1000-watts).

Case 1.—Given Current and Pressure to Find Watts Lost or Expended:

The watts expended in any circuit equals the product of the current and the pressure causing it to flow, Formula (62).

$$W = E \times I.$$

Prob. 82.—Find the energy expended in a lamp requiring 110 volts and ½ ampere.

By Formula (62)) $W = E \times I = 110 \times \frac{1}{2} = 55$ **watts.**

Case 2.—GIVEN CURRENT AND RESISTANCE, TO FIND THE ENERGY EXPENDED IN WATTS:

The watts lost or expended in any circuit are equal to the current squared multiplied by the resistance. This is often called the I-square R loss.

$$W = I^2 \times R \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (68).$$

This formula is obtained by substituting the value of $E = I \times R$ in Formula (62) $W = E \times I$, which gives $W = I \times R \times I = I^2 R$.

Prob. 83: The resistance of the field magnets of a dynamo is 220 ohms and the magnetising current, 2 amperes. What energy is expended?

By Formula (68) $W = I^2 R = 2 \times 2 \times 220 = 880$ watts.
$R = 220$ ohms, $I = 2$ amperes.

Case 3.—GIVEN RESISTANCE AND PRESSURE, TO FIND THE WATTS EXPENDED:

The watts lost or expended in any circuit are equal to the square of the pressure divided by the resistance.

$$W = \frac{E^2}{R} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (69).$$

This formula is obtained by substituting the value of $I = \frac{E}{R}$ in Formula (62) $W = E \times I$, then $W = E \times \frac{E}{R} = \frac{E^2}{R}$.

Prob. 84: The hot resistance of a 110-volt incandescent lamp is 220 ohms. What energy is expended in the lamp every second it burns?

By Formula (69) $W = \frac{E^2}{R} = \frac{110 \times 110}{220} = 55$ watts.
$E = 110$ volts, $R = 220$ ohms.

Compare this result with Prob. 82.

Case 4.—GIVEN WATTS EXPENDED AND CURRENT, TO FIND THE RESISTANCE:

The resistance is equal to watts expended divided by the square of the current.

$$R = \frac{W}{I^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (70).$$

This formula is found by transposing Formula (68).

Prob. 85: A 55-watt incandescent lamp requires ½ ampere. What is its resistance?

By Formula (70) $R = \frac{W}{I^2} = \frac{55}{.5 \times .5} = \frac{55}{.25} = 220$ ohms.
$W = 55$ watts, $I = \frac{1}{2}$ ampere.

Compare this answer with Probs. 82 and 83.

Case 5.—GIVEN WATTS EXPENDED AND RESISTANCE, TO FIND THE CURRENT:

The current equals the square root of the watts divided by the resistance.

$$I = \sqrt{\frac{W}{R}} \quad \ldots\ldots\ldots\ldots (71).$$

This formula is obtained by transposing Formula (68).

Prob. 86: If the hot resistance of a 55-watt lamp is 220 ohms, what current will it require?

By Formula (71) $I = \sqrt{\frac{W}{R}} = \sqrt{\frac{55}{220}} = \sqrt{\frac{1}{4}} = \frac{1}{2}$ ampere.

$W = 55$ watts, $R = 220$ ohms. Compare with Probs. 82, 84, and 85.

Case 6.—GIVEN WATTS EXPENDED AND PRESSURE, TO FIND RESISTANCE:

The resistance equals the square of the pressure divided by the watts expended.

$$R = \frac{E^2}{W} \quad \ldots\ldots\ldots\ldots (72).$$

This formula is obtained by transposing Formula (69).

Prob. 87: What is the resistance of a 55 watt, 110 volt incandescent lamp?

By Formula (72) $R = \frac{E^2}{W} = \frac{110 \times 110}{55} = 220$ ohms.
$E = 110$ volts, $W = 55$ watts.

Case 7.—GIVEN WATTS EXPENDED AND RESISTANCE, TO FIND THE PRESSURE:

The pressure is equal to the square root of the product of watts and resistance.

$$E = \sqrt{W \times R} \quad \ldots\ldots\ldots\ldots (73).$$

Prob. 88: What pressure must be applied to an incandescent lamp of 220 ohms hot resistance so that it will receive 55 watts?

By Formula (73) $E = \sqrt{W \times R} = \sqrt{55 \times 220} = 110$ volts.
$W = 55$ watts, $R = 220$ ohms.

225. Electrical Power Formulæ.—

The above cases are summarized as follows:

$W = E \times I$ . . . . Formula (62).

$W = I^2 \times R$ . . . . " (68).

$W = \frac{E^2}{R}$ . . . . " (69).

$E = \frac{W}{I}$ . . . . " (64).

$E = \sqrt{W \times R}$ . . . . " (73).

$E = I \times R$ . . . . " (29).

$I = \frac{E}{R}$ . . . . " (28).

$I = \frac{W}{E}$ . . . . " (63).

$I = \sqrt{\frac{W}{R}}$ . . . . " (71).

$R = \frac{E}{I}$ . . . . " (30).

$R = \frac{E^2}{W}$ . . . . " (72).

$R = \frac{W}{I^2}$ . . . . " (70).

If it is desired to use the larger unit of power, the horse power, the above formulæ may be changed by remembering that 1 horse power = 746 watts, and they will then be as follows:

From Formula (65) $H. P. = \frac{E \times I}{746}$ . . . . (65).

From Formula (68) $H. P. = \frac{I^2 \times R}{746}$ . . . . (74).

From Formula (69) $H. P. = \frac{\frac{E^2}{R}}{746} = \frac{E^2}{746 \times R}$ . . . . (75).

From Formula (65) $E = \frac{H. P. \times 746}{I}$ . . . . (76).

From Formula (65) $I = \frac{H. P. \times 746}{E}$ . . . . (77).

From Formula (75) $R = \frac{E^2}{H. P. \times 746}$ . . . . (78).

From Formula (66) $K. W. = \frac{E \times I}{1000}$ . . . . (66).

From Formula (68) $K. W. = \frac{I^2 \times R}{1000}$ . . . . (79).

From Formula (69) $K. W. = \frac{E^2}{1000 \times R}$ . . . . (80).

226. Power from Cells.—The amount of power that can be furnished by a cell is directly proportional to the square of its E. M. F. divided by its internal resistance and is equal to the number of watts expended by the cell on short circuit. Let W represent the power in watts from a single cell, then from Formula (72) we get

$$W = \frac{E^2}{r} \quad \ldots\ldots \quad (81).$$

The power obtained from any number of similar cells is equal to the power of one cell multiplied by that number, and is independent of the grouping, provided that it is symmetrical. For example, the amount of power a Leclanche cell can furnish if the E. M. F. is 1.5 volts and internal resistance .25 ohm $= \frac{E^2}{r} = \frac{1.5 \times 1.5}{.25} = 9$ watts.

The power furnished by ten cells would be $10 \times 9 = 90$ watts. If arranged all in series then the total E. M. F. $=$ 15 volts and total internal resistance $= 2.5$ ohms, Formulæ (36) and (37), and $W = \frac{E^2}{r} = \frac{15 \times 15}{2.5} = 90$ watts.

If arranged all in parallel then the total E. M. F. $= 1.5$ volts and the internal resistance $= .025$, Formulæ (37) and (38), and $W = \frac{E^2}{r} = \frac{1.5 \times 1.5}{.025} = 90$ watts as before, also 2 cells in series and 5 groups in parallel equal 90 watts as before, etc. In the above cases all the energy is expended inside the cell. For a steady current of maximum value through the external circuit, its resistance should be equal to the internal resistance of the battery. This is also the condition for a maximum rate of working or activity. The maximum economy for installing a number of cells required for any given rate of working is attained when the work is performed satisfactorily by the minimum number of cells. This condition is obtained when the total power the cells can maintain on short circuit is equal to four times the power required from them for the external circuit.

To find the number of cells required for maximum economy of installation for any power to be developed: *Multiply 4 times the power in watts required by the internal resistance of one cell and divide the product by the square of the E. M. F. of one cell.*

Let N = number of cells required;
W = watts required in external circuit;
r = internal resistance of one cell;
E = E. M. F. of one cell.

$$N = \frac{4 \times W \times r}{E^2} \quad \ldots\ldots\ldots (82).$$

Prob. 89: How many chromic acid cells will be required for maximum economy of first installation to light a 12-watt incandescent lamp? Each cell has an E. M. F. of 2 volts and an internal resistance of .5 ohm.

By Formula (82) $N = \frac{4 \times W \times r}{E^2} = \frac{4 \times 12 \times .5}{2 \times 2} = 6$ cells.

$W = 12$ watts, $E = 2$ volts, $r = .5$ ohm.

The cells in Prob. 89 could be arranged in any symmetrical combination to produce the 12 watts in the external circuit. Suppose the 12-watt-lamp required 6 volts, then all the cells would be placed in series, Fig. 201. The E. M. F. of the battery would be 12 volts and the internal resistance $6 \times .5 = 3$ ohms, or the energy expended on short circuit by Formula (81) $W = \frac{E^2}{r} = \frac{12 \times 12}{3} = 48$ watts, or four times the energy required by the lamp. The resistance of the lamp is 3 ohms, Formula (72), and when connected to the 6 cells in series will receive 2 amperes, Formula (37). The pressure sending the current through the cells is $I \times r = 2 \times 3 = 6$ volts, or one-half the E. M. F., and 6 volts are also maintained across the lamp terminals. The external power is thus $2 \times 6 = 12$ watts and the watts lost in the cell 12 watts, or the total watts = 24, or one-half the power the cells could deliver on short circuit.

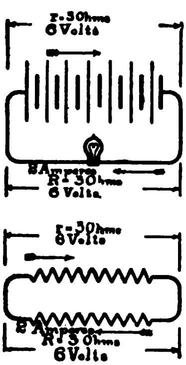


Fig. 201.—"Volts Lost" on the Internal Resistance.

227. Efficiency of a Battery.—By efficiency is meant the relation of the useful work done to the total energy expended. A perfect battery, or dynamo (that is, one with no internal resistance), would deliver all of the energy to the external circuit, but as some portion of it is lost in the internal resistance the useful energy is always less than the total energy expended. If the total energy expended is represented

by 100, and one-half of this amount is unavailable for useful work, the efficiency would be 50 per centum or 50 per cent. In no machine, then, can the efficiency be 100 per cent.

TO FIND THE EFFICIENCY OF A BATTERY:

Divide the resistance of the external circuit by the resistance of the external circuit plus the resistance of the battery.

$$\text{Eff.} = \frac{R}{R + r} \quad \ldots\ldots\ldots\ldots \quad (83).$$

Prob. 90: What is the efficiency of the battery in Prob. 89? The total resistance of the battery is 3 ohms and the resistance of the lamp is 3 ohms.

By Formula (85) $\text{Eff.} = \frac{R}{R + r} = \frac{3}{3 + 3} = .50$ or 50%.

The total watts expended in ¶ 226 are 24, and the useful watts in the lamp 12, so that the efficiency is the ratio of

$$\frac{\text{Useful watts}}{\text{Total watts expended}} = \frac{12}{24} = .50 = 50\%, \text{ as before.}$$

Let W = useful energy expended (in watts);
w = useless energy expended (in watts).

Then, $$\text{Eff.} = \frac{W}{W + w} \quad \ldots\ldots\ldots\ldots \quad (84).$$

QUESTIONS.

1. What is the difference between force and work?
2. Define mass; energy; power; weight.
3. What is the unit of (a) mechanical power? (b) Of mechanical work? (c) Of electrical work? (d) Of electrical power?
4. Cite examples illustrating the conservation and correlation of energy.
5. How would you ascertain, by experiments, the mechanical equivalent of work performed by an electric current?
6. What is the difference between a kilowatt and a kilowatt-hour?
7. A battery used in electroplating has an efficiency of 70 per cent. What do you understand by this statement?

PROBLEMS.

1. How much electrical energy is expended in maintaining a 16 candle power incandescent lamp, supposing that it has a resistance of 220 ohms (hot) and is taking 0.5 ampere? How many watts per candle power? How many such lamps can be maintained at full candle power by one mechanical horse power? *Ans.* 55 watts; 3.43 watts; 13 lamps.

2. A number of 100-volt incandescent lamps are being lighted by a dynamo generating 112 volts at the brushes. The resistance of the leads carrying current to the lamps is .05 ohm. Each lamp requires 50 watts. How many lamps are burning? *Ans.* 480 lamps.

3. (*a*) What size of generator (kilowatt capacity) should be purchased for a 500 light installation, supposing that standard 55 watt, 16 candle power incandescent lamps are to be adopted? (*b*) What would be the K. W. capacity of a motor required to be substituted for a 25 horse power gas engine. *Ans.* (*a*) 27.5 K. W.; (*b*) 18.65 K.W.

4. In constructing a solenoid and core to actuate a lever, 500 feet of number 18 B. & S., D. C. C. magnet wire were wound upon a brass spool. A table of heating limits gives 2 amperes as a safe carrying capacity for this size of wire under these conditions. Using this current, how much extra resistance must be added to place the coil across a line of 110 volts potential difference? *Ans.* 51.68 ohms.

5. The above solenoid is to operate in series with the field magnets of a dynamo having 30 ohms resistance. (*a*) How much extra resistance must now be added to place the fields and coil in series across the above mains so as to receive the same current? (*b*) How many feet of No. 18 B. & S. iron wire are required to construct a rheostat for the extra resistance in this problem? (*c*) If the average length of each turn on the solenoid is 4 *inches*, what is the magnetising force? (*d*) How much energy is consumed in the solenoid? *Ans.* (*a*) 21.68 ohms; (*b*) 555 feet; (*c*) 3000 A. T.; (*d*) 13.28 watts.

6. A street car is driven by two four-pole series motors. Each field magnet has a resistance of .125 ohm, the armature .125 ohm and an extra rheostat (diverter) has a resistance of 4 ohms. E. M. F. between trolley wire and rails is 500 volts. Neglecting the counter E. M. F. of the motors, find the current the motors will receive in the following positions of the controller switch: (*a*) First point: Both motors in series, all field coils in series, extra resistance in series. (*b*) Fourth point: Both series motors in parallel and the extra resistance in series with them. (*c*) What power is the car receiving on the fourth point? (*d*) Make a sketch of both controller combinations. *Ans.* (*a*) 95.238 amperes; (*b*) 115.942 amperes; (*c*) 77.7 H. P.

7. An electric automobile is equipped with 40 storage batteries which are connected, through the controller switch, for the first speed, 20 cells in series and two groups in parallel. Each cell has an E. M. F. of 2 volts and an internal resistance of 0.1 ohm. The resistance of the motors, extra resistance and leads at this combination is 0.5 ohm. (*a*) What is the value of the current required to start the vehicle? (*b*) How much energy is expended at the start? *Ans.* (*a*) 26.6 amperes; (b) 1064 watts.

8. While visiting an electric light station you note the following indications of instruments on the switchboard: voltmeter 115, ammeter 330. The plant operates the two-wire direct current system and uses 55-watt, 110-volt incandescent lamps. (*a*) How many lamps, at the instant of reading, are burning? (*b*) What is the load on the generator expressed in kilowatts and electrical horse power? *Ans.* (*a*) 660 lamps; (*b*) 37.95 K. W.; 50.87 H. P.

9 A compound wound dynamo is connected to a circuit to which the following apparatus is wired: 150 incandescent lamps, each re-

quiring .6 ampere ; 3 arc lamps, 10 amperes each ; various electrical cooking and heating appliances requiring when all are at work 20.5 amperes ; two electroplating and electrotyping baths arranged in series across the mains and taking a maximum current of 5 amperes ; 10 storage batteries in series with a lamp bank resistance across the mains and requiring a charging current of 10 amperes. The two-wire direct current system is used and a constant potential difference of 110 volts is maintained between mains. What is the output of the generator in electrical horse power, supposing that the maximum current ever required is 75 per cent. of that taken when the whole installation is at work? *Ans.* 17.19 H. P.

10. Two arc lamps of 900 and 1200 C. P., having a hot resistance of 7.5 and 4.5 ohms respectively, and an incandescent lamp with 30 ohms resistance, are all placed across a pair of mains. An ammeter in the main circuit indicates 17.5 amperes. (*a*) What current is each lamp receiving? (*b*) What is the difference of potential between the mains? (*c*) What power is absorbed by each lamp? (*d*) How many candles per watt in the 1200 C. P. lamp? *Ans.* (*a*) 6, 10, 1.5 amperes; (*b*) 45 volts P. D.; (*c*) 270, 450, 67.5 watts ; (*d*) 2.6 C. P.

11. The mean effective steam pressure from an indicator card is 50 pounds ; the speed of the engine, 290 revolutions ; length of stroke 10 inches ; area of piston head 0.75 square foot. What horse power is developed by the engine? *Ans.* 79.06 H. P.

12. How many watts are expended in an arc lamp having a hot resistance of 4.5 ohms and requiring 50 volts? *Ans.* 555.55 watts.

13. What is the current flowing through an electromagnet having a resistance of 50 ohms and requiring 200 watts? *Ans.* 2 amperes.

14. What is the maximum power obtainable from a Grenet cell of 2 volts, E. M. F. and an internal resistance of .02 ohm ? *Ans.* 200 watts.

15. How many cells are required for maximum economy of installation to operate an electromagnet requiring 20 watts? Each cell has an E. M. F. of 2 volts and an internal resistance of .5 ohm. *Ans.* 10 cells.

16. If the magnet in question 15 has a resistance of 5 ohms and requires 10 volts, what is the best arrangement of the cells and what is the efficiency? *Ans.* 10 cells in series, 50%.

LESSON XX.

MEASUREMENT OF PRESSURE.

Electromotive Force and Potential Difference—Hydraulic Analogy to Illustrate "Volts Lost"—Volts Lost in an Electric Circuit—Distribution of Potential in a Circuit—Variation of Potential Difference with Variation of External Resistance—Table XIV. Variation of Current, Pressure and Resistance—Measurement of E. M. F. and P. D.—Construction of Voltmeters—Weston Voltmeter—Connecting Voltmeters—Measuring High Voltages with a Low Range Instrument—Measurements with a Voltmeter—Volts Lost in Wiring Leads—Comparison of E. M. F. of Cells by the Potentiometer—Questions and Problems.

228. Electromotive Force and Potential Difference.— *Volts lost or "Drop" in a Circuit.*—Electromotive force is the total force generated. potential difference is any part of the total E. M. F., ¶ 70. The E. M. F. of any generator is not available for use in the external circuit, since part of it is required to cause the current to flow through the internal resistance of the generator (battery or dynamo). By the expressions *fall of potential, "drop" or "volts lost"* in any part of a circuit is meant that portion of the E. M. F. which is used in causing the current to flow between the two points considered. For example, the "volts drop" across a lamp means the potential difference across the lamp terminals, it is the force which is causing the current to flow through the lamp. Two "volts lost on the line" means that this much pressure is lost or used in sending the current through the line. The E. M. F. is the sum of all the potential differences, as, the drop on the line plus the drop on the lamp plus the drop on the internal resistance of the generator. The term "*volts lost*" or "*volts drop*" implies that energy is lost, since energy is the product of volts and current, Formula (62); pressure could not be lost in any circuit unless a current had been transmitted by it.

229. Hydraulic Analogy to Illustrate "Volts Lost." A hydraulic analogy may assist somewhat in understanding the fall of potential or volts drop in an electric circuit. In Fig. 202, T is a

cylindrical tank filled with water under pressure due to the weight of the piston P, and AB is a pipe for transmitting the water to point B. With the valve at B closed the pipe is full of water, but there is no current through it. The gauges at A and B, each indicate 60 pounds per square inch, which represents the water-motive-force or power to move the water. When the valve is opened quarter-way

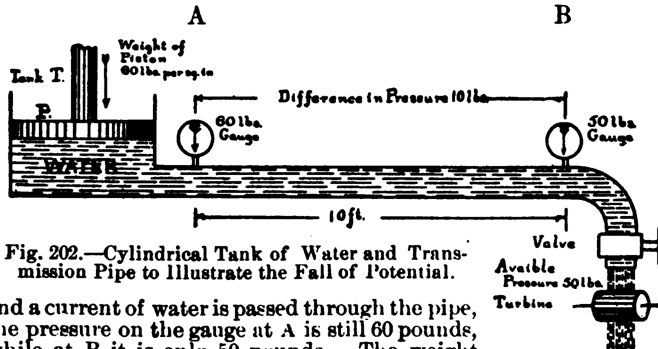


Fig. 202.—Cylindrical Tank of Water and Transmission Pipe to Illustrate the Fall of Potential.

and a current of water is passed through the pipe, the pressure on the gauge at A is still 60 pounds, while at B it is only 50 pounds. The weight of water is neglected. There is thus a difference in pressure of 10 pounds, between the two points A and B, and this force has been used or lost in overcoming the friction or resistance offered by the sides of the pipe to the running water. The available pressure at the B end of the pipe, which might be used for driving a turbine, is only 50 pounds, while the total pressure is 60 pounds. There is thus not a loss of quantity of water, but a loss of energy, as work has been performed in moving the water. Suppose the pipe to be of uniform bore and 10 feet long, then a gauge inserted at a point one foot from A would indicate 59 pounds; at two feet, 58 pounds, etc.; or there is a gradual fall or drop of pressure along the pipe which is directly proportional to the length when the resistance is uniform, or a drop of one pound per foot in length.

The difference in pressure between any two points is the pressure required to send the current between these points, and is found by subtracting the pressure of that gauge which is more distant from the generating source from the pressure of the gauge nearer to it. The valve is now opened half way and the gauge at A still indicates 60 pounds, while that at B now indicates 40 pounds. A difference in pressure of 20 pounds is required to cause the increased current to flow through the pipe, leaving only 40 pounds available pressure to be applied to the turbine at B. A force of two pounds is required to send the increased current through each foot of the pipe, and the sum of the pressures lost in the 10 feet equals 20 pounds, or the difference in pressure between the points A and B. If the valve at B is opened still further the difference in pressure between A and B will be greater, since more water will flow, and the available pressure at B will be correspondingly less. If the transmitting pipe considered above is replaced by one much larger in diameter, the resistance will

be less and less pressure therefore will be lost in transmitting the water, so that a greater available pressure will result.

Suppose that the pipe AB is composed of several pieces of different sizes joined together, Fig. 203; with no current flowing the pressure at gauge B is equal to that at A. With the valve opened quarter way gauge A indicates 60 pounds and gauge B 50 pounds, as before, or a loss in pressure between the two points A and B of 10 pounds, which causes the current to flow between them. While the current of water may be the same as before and the total pressure lost also the same, the distribution of the lost pressure is not the same since the resistance of the pipe is not uniform, it being practically a number of pipes of different sizes, and therefore different resistances, connected in series. The greatest difference in pressure will be between points having the greatest resistance, such as the length of pipe of small diameter, where four pounds are required to send the current of water through this section of the pipe, while only two pounds are required to send the same current through the larger adjacent section. The opposition to be overcome in the pipe of smaller diameter is twice as great as in the larger pipe, since twice the pressure is required to send the *same* current through it. In hydraulics, calculations are made to deliver water at a certain rate of flow and under a certain pressure, in which case the pressure and energy lost in transmitting the water must be considered. The same is true in calculating the sizes of pipes for gas lighting, and of wires for carrying electric currents, ¶ 239.

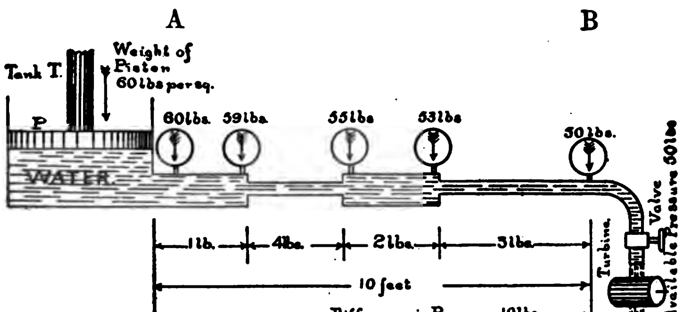


Fig. 203.—Hydraulic Analogy of the Fall of Potential.

230. Volts Lost in an Electric Circuit.—Consider now an electric circuit in which a generator (battery or dyamo) is supposed to maintain a constant pressure of 60 volts between two parallel lines at the point A, Fig. 204, as indicated by a high resistance galvanometer or voltmeter. With no current flowing from the generator the voltmeter will indicate 60 volts at point B (neglecting the pressure used to

transmit the small current used by the voltmeter). By closing the switch at B one lamp is lighted, and an ammeter indicates 1 ampere flowing through the circuit. The voltmeter at A still indicates 60 volts, but the voltmeter at B only 50 volts. There is, therefore, a difference in pressure between points A and B of 10 volts, which is used in overcoming the resistance of the line and causing the one ampere to flow through it. The available pressure at point B to perform useful work in the lamp is, therefore, only 50 volts and causes one ampere to flow through it. There is no loss of current but a loss of energy on the line ($10 \times 1 = 10$ watts) that is, work has been performed in transmitting the current from A to B just as in the case of the water. If 10 volts are required to send one ampere through the line, by Formula (30), its resistance will be 10 ohms.

If the wire is of uniform area and 10 feet in length, from A to B, the voltmeter will indicate 59 volts when placed across the line at points 1–1, one foot distant from A; 58 volts at 2 feet, or points 2–2, etc.; or the fall of potential along the line is directly proportional to its length and resistance. Since the total resistance of the line is 10 ohms the resistance of one wire is 5 ohms and the difference in potential required to send one ampere through 5 ohms is $E = I \times R = 1 \times 5 = 5$ volts. (Formula 29.) A voltmeter placed across one side of the line to include 10 feet of its length will indicate a potential difference of 5 volts drop or loss on this side, and the same drop on the other side of the line. Since there are 5 volts drop on 10 feet of wire of uniform resistance the drop per foot will be $\frac{1}{2}$ volt, or 1 volt for every 2 feet, etc. The voltmeter when placed in parallel with any length of the wire will indicate the difference of potential between the points included.

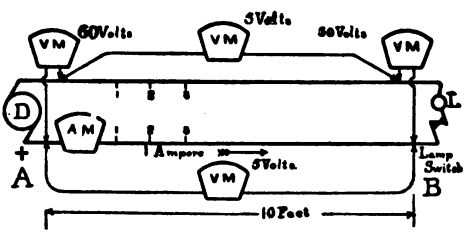


Fig. 204.—" Volts Drop " in an Electric Circuit.

Now turn on the switch with a second lamp of such resistance that the ammeter indicates 2 amperes, Fig. 205. The voltmeter at A still indicates 60 volts as before, but that at B

now indicates only 40 volts. The difference in pressure between points A and B is 20 volts, since twice the current through the same resistance requires double the pressure to be applied. The available pressure applied to the lamps is 40 volts. If the wires considered above were just double the area, only one-half of the pressure would be lost on the leads, and therefore one-half of the energy lost, and a higher available P. D. at point B would be maintained.

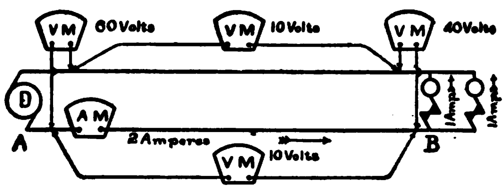


Fig. 205.—" Volts Drop" in an Electric Circuit.

Suppose the transmitting line to be composed of several wires of different sizes connected in series as represented by the heavy and thin lines in Fig. 206. With one lamp connected at B, the voltmeter may read 50 volts, as before, but the fall of potential or drop on the line, 10 volts, will not now be uniform, since the resistance is not uniform. The greatest potential difference or drop will be between the points of highest resistance. Consider the equal lengths of wire E F and F G of *unequal areas*. The *current* is the *same* through each, but the voltmeter indicates 3 volts when connected across points E F, and only 1 volt when placed across points F G. The thin wire E F has three times the resistance of the wire F G, since three times the pressure is required to send the same current through it. The drop in volts in other portions of the circuit may be measured in the same manner, the sum of all the readings being equal to the total loss on the line, or 10 volts. The watts lost in E F are also three times as great as in F G, or three watts and one watt respectively, Formula (62). The total watts generated at point A with one lamp in circuit $= 60 \times 1 = 60$ watts. *The watts lost on the line* $= 10 \times 1 = 10$ watts, thus 50 watts are expended in the lamp. By Formula (84) the efficiency of this part of the circuit will be $50 \div 60 = .83\frac{1}{3} = 83\frac{1}{3}$ %.

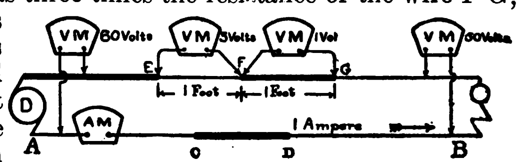


Fig. 206.—" Volts Drop" in an Electric Circuit.

231. Distribution of Potential in a Circuit.—In the above illustrations the pressure was assumed to be maintained constant at point A. Consider now a battery or dynamo D, Fig. 207, with an internal resistance (r) of 4 ohms connected to one lamp at B, 10 feet distant from A. The voltmeter at A indicates 60 volts as before, and with one ampere flowing through the lamp, 50 volts at B. Ten volts are required to send one ampere through the lead wires, and since the internal resistance of the generator is 4 ohms, 4 volts will be required to send one ampere through it,

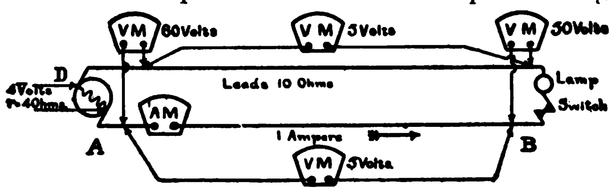


Fig. 207.—E. M. F. and Potential Difference in an Electric Circuit.

Formula (29). The total pressure or E. M. F. is, therefore, 4 + 10 + 50 or 64 volts. The voltmeter across the generator terminals, however, indicates the potential difference or that portion of the E. M. F. available in the external circuit, 60 volts. If the lamp at B is turned out the voltmeters at both points A and B will indicate 64 volts, or the E. M. F. of the source of electricity. Now connect two lamps in circuit, Fig. 208; the resistance of one lamp is 50 ohms, and of two in parallel it is 25 ohms, Formula (43). The total resistance of the circuit, R + r = 10 + 25 + 4 = 39 ohms, and the current, therefore, equals 64 ÷ 39 or 1.64 amperes, Formula (28). The voltmeter at B indicates 1.64 × 25 = 41 volts, Formula (29), while voltmeter at A indicates 1.64 × (10 + 25) = 57.4 volts potential difference at the generator terminals. The drop on the internal resistance is 4 × 1.64 = 6.56 volts or total E. M. F. 6.56 + 57.4 = 64 volts (nearly). If the lamps require 50 volts to send sufficient current through them to give the proper amount of light, with 40 volts across

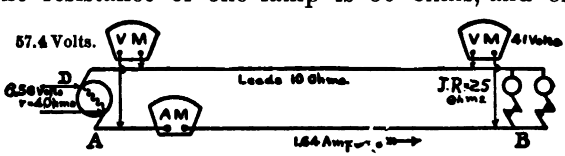


Fig. 208.—E. M. F. and Potential Difference in Electric Circuit.

their terminals they will now burn dimly, since each lamp does not receive one ampere, as before. The total E. M. F. must be increased, say by adding more cells in series, or increasing the field strength of the dynamo, if 50 volts are to be maintained across the two lamps in parallel. If one lamp is then turned out the other lamp receives a greater pressure than 50 volts, since the drop on the leads and internal resistance is less when the current through them is diminished. The E. M. F. must therefore be decreased as the current is decreased and increased when the current increases. In a battery installation for lighting lamps a special switch is designed to connect, or disconnect several end-cells as the voltage regulation may require. This switch is called an *end-cell switch*. In a dynamo the E. M. F. is varied by increasing or decreasing the field strength of the electromagnets.

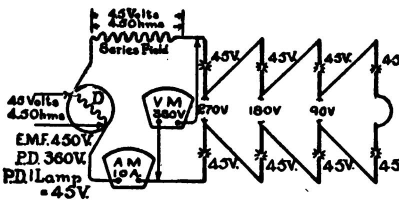


Fig. 209.—E. M. F. and Potential Difference in a Series Arc Light Circuit.

Prob. 91: Eight arc lamps are connected in series to a series dynamo, Fig. 209, each lamp requires 45 volts and 10 amperes. The resistance of the series field is 4.5 ohms and the armature has a resistance of 4.5 ohms. (a) What pressure will be indicated by a voltmeter placed across the brushes? (b) What is the E. M. F. of the generator? (c) How much energy is lost in the internal and external circuits? (d) What is the electrical efficiency? See Fig. 209.

By Formula (30) $R = \frac{E}{I} = \frac{45}{10} = 4.5$ ohms per lamp.

Resistance of 8 lamps in series $= 8 \times 4.5 = 36$ ohms.

By Formula (29) $E = I \times R = 10 \times 36 = 360$ volts potential difference (a).

Total resistance, $r + R = 4.5 + 4.5 + 36 = 45$ ohms.

By Formula (33) E. M. F. $= I \times (R + r) = 10 \times 45 = 450$ volts (b).

By Formula (62) $W = E \times I = 360 \times 10 = 3600$ watts external circuit.

By Formula (62) $W = E \times I = 450 - 360 = 90$ volts $\times 10 = 900$ watts internal circuit (c).

By Formula (84). $\text{Eff.} = \frac{W}{W + w} = \frac{3600}{3600 + 900} = .80 = 80$ per cent. **(d).**

232. Variation of Potential Difference with Variation of External Resistance.—

Exp. 64: Connect a voltmeter to a Grenet cell and also a variable resistance, R, in series with an ammeter, Fig. 210. With switch, S, open, the voltmeter indicates 2 volts or the E. M. F. of the cell. Adjust arm A of the rheostat so that a very high resistance will be connected to the cell, say 100 ohms, when switch, S, is closed. The voltmeter now indicates 1.999 volts or the potential difference is nearly equal to the E. M. F. when the external resistance is high, since very little current flows. Now reduce R to about 9.6 ohms; if the cell's resistance $= .4$ ohm, $r + R = 10$ ohms and the current $= \frac{2}{10} =$ .2 ampere. The voltmeter indicates $I \times R = .2 \times 9.6 = 1.92$ volts potential difference which is causing .2 ampere to flow through 9.6 ohms, the remaining .08 volt is required to send the same current through the internal resistance. Reduce the external R to .4 ohm and the voltmeter indicates 1 volt P. D. Since the external resistance is now equal to the internal resistance there is 1 volt drop inside the cell. Short circuit the cell by a very low resistance and the voltmeter indicates practically zero, the current from the cell is a maximum and all of the E. M. F., 2 volts, is used in sending the current through the cell's internal resistance. The preceding experiments may be summed up in the following table, which can be verified by the apparatus in Fig. 210:

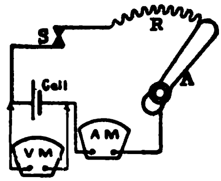


Fig. 210.—Variation of P. D. and Current with a Variation of Resistance.

Table XIV.—Variation of Current, Pressure, and Resistance.

Ohms External Circuit, R.	Volts Across Battery, P. D.	Amperes, I.
Infinity	Equal to E. M. F.	0
Great compared with r	Very little less than E. M. F.	Small
R, say any value	$\frac{R}{R+r} \times$ E. M. F.	$\frac{\text{E. M. F.}}{R+r}$
Small compared with r	Small	Large
0	0	Maximum and equal to $\frac{\text{E. M. F.}}{r}$

The following formulæ derived from Ohm's Law will be found useful in calculating the internal resistance and potential difference:

Let E = E. M. F. in volts;
P. D. = Potential difference (P. D.) in volts.

$$I = \frac{P.D.}{R},$$

$$I = \frac{E - P.D.}{r} \quad \ldots\ldots\ldots\ldots \quad (85).$$

$$I = \frac{E}{R + r}.$$

By combining the first and third equations we get,

$$\frac{P.D.}{R} = \frac{E}{R + r},$$

$$\text{or } P.D. = \frac{R \times E}{R + r} \quad \ldots\ldots\ldots\ldots \quad (86).$$

From Formula (85) $r = \frac{E - P.D.}{I}$ . . . . (87).

By Formula (87) a cell's internal resistance may be measured by noting the voltmeter and ammeter readings when it is connected, as in Fig. 210.

Prob. 92: The E. M. F. of a Leclanche cell is 1.4 volts; P. D., measured at the battery terminals when .8 ampere is flowing, is 1 volt. What is the cell's internal resistance?

By Formula (87) $r = \frac{E - P.D.}{I} = \frac{1.4 - 1.}{.8} = \frac{1}{2}$ ohm.

$E = 1.4$ volts, P. D. $= 1$ volt, $I = .8$ ampere.

Prob. 93: The E. M. F. of a dynamo is 112 volts; resistance of lamp circuit 5 ohms; resistance of armature .05 ohm. What P. D. will a voltmeter indicate when placed across the brushes?

By Formula (86) P. D. $= \frac{R \times E}{R + r} = \frac{5 \times 112}{5 + .05} = 110.8$ volts.

$E = 112$ volts, $R = 5$ ohms, $r = .05$ ohm.

233. Measurement of E. M. F. and P. D.—Consider first the following hydraulic analogy in which it is desired to measure the true water pressure at the point C in a pipe, Fig. 211, through which a current of water is flowing from point A to point B. Instead of using a spring gauge which consumes no water in making the measurement, we will use a turbine wheel at point C. A jet of water is therefore forced against the wheel, which revolves at a particular speed for a given pressure at point C, say, 1600 revolutions per minute, corresponding to a pressure of 50 pounds per square inch at C. *Is this the accurate pressure at point C, or is it the pressure that would be recorded by a spring gauge if inserted at point C?* No. The turbine in measuring the pressure will increase the flow of water at point C, as some water must necessarily discharge

through it. The accurate pressure will not be recorded, but a lower pressure than that which exists when the turbine is not connected. The increased current of water through the pipe from A to C, *due* to the turbine outlet, causes a greater loss in pressure. If the turbine were made exceptionally small and sensitive so that a very minute stream of water from the outlet would actuate it, it would more nearly record the true pressure at point C, since very little more current would then flow than when it was disconnected. This turbine pressure meter must therefore be constructed so that only a very small amount of water will be used by it in measuring the water pressure.

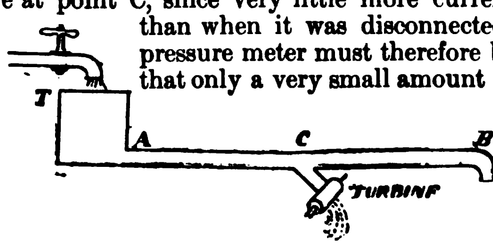


Fig. 211.—Measurement of Hydraulic Pressure.

To measure the electrical difference of potential between two points requires a galvanometer constructed with a very high resistance, so that only a very minute current will flow through it, at the same time the current must be of sufficient strength to actuate the movable system, which is generally quite sensitive, ¶ 180. *To measure electrical pressure some current must therefore be used, and the true pressure will be greater than the indicated pressure by an amount equal to the volts lost on the line and generator which are required to transmit the voltmeter current to the instrument. The less this current the more accurate the indication, consequently the best voltmeters have a very high resistance and their current is practically negligible.* When a voltmeter is placed in parallel with any part of a circuit the resistance of the circuit is practically the same as before, since the voltmeter resistance is so very high the current in the circuit is not materially changed, and the calibrated indication records, not the current in the circuit, or the current through the voltmeter, but the difference in pressure between the voltmeter terminals. The movement of its magnetic system, of course, depends upon the current flowing through the voltmeter, but the scale is calibrated by applying known E. M. F.'s to its terminals and marking the position of the needle with reference to the scale for each particular pressure applied, ¶ 180. In an ammeter the whole current passes through the instrument, or its

shunt, and the instrument measures the current. A voltmeter measures the current flowing through it, but the *calibration is in terms of the pressure causing this current to flow.* See Exp. 57, ¶ 182.

234. Construction of Voltmeters.—The same principles employed in the construction of ammeters, ¶ 204, etc., are employed in constructing voltmeters, the only difference being that the windings are of very fine wire, suitable to the small current that is to be carried, and that extra resistance coils are generally added in series with the voltmeter coils to produce an instrument of very high resistance, for the reasons already given. The method of calibration is given in ¶ 182.

Fig. 212.—Weston Double Scale Voltmeter.

235. Weston Voltmeter.—The same construction is employed in this make of voltmeter as in the Weston ammeter, ¶ 208, extra resistance being connected in series with the movable coil and the terminals brought out to binding posts, Fig. 213. A double-scale Weston voltmeter is shown in Fig. 212, suitable for use with pressures as high as 150 volts. The 150 volt coil terminates in the lower right and left-hand binding posts, and the current enters by the right-hand post marked +. A push-button above this post serves to close the circuit. The resistance of the 150 volt coil is about 150,000 ohms, and there are 150 divisions on the upper, or black ink scale, or one division per volt. The 15 volt coil terminates in the lower right-hand and upper left-hand posts, and has a resistance of about 1500 ohms. There are ten divisions on this red ink scale per volt, so that one-tenth, five-hundredths

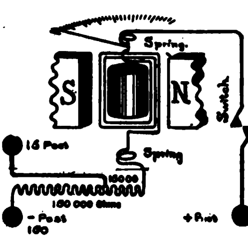


Fig. 213.—Connections of Weston Double Scale Voltmeter.

or even twenty-five thousandths of a volt may easily be read from this scale. In using a double scale voltmeter, *if in doubt about the value of the voltage* to be measured, *always use the higher reading scale first*, then if the value is below the limit of the low reading scale, the left-hand terminal may be readily changed to the upper post marked 15. If 150 volts are directly applied to the low reading scale the instrument will be seriously damaged and probably the insulation destroyed by a larger current flowing through it than the windings will carry. This wire may be as small as .001 inch in diameter. For the same reason any voltmeter should not be subjected to a higher voltage than is indicated upon its scale. Voltmeters are calibrated by means of standard cells and are made up according to the range of the instrument desired, by means of the extra resistance to be added. In a *milli-voltmeter* the scale is graduated to read in divisions, representing one-thousandth part of a volt, or one millivolt

With a good voltmeter many practical electrical measurements may be made, some of which are given in the Appendix.

Prob. 94: A 150 volt coil of a Weston voltmeter has a resistance of 150000 ohms. What current will it receive when placed across a circuit of 100 volts P. D.?

By Formula (28) $I = \frac{E}{R} = \frac{100}{150000} = .00066$ ampere.

$E = 100$ volts, $R = 150000$ ohms.

236. Connecting Voltmeters.—Voltmeters are connected directly across the line, the P. D. of which is required, or in parallel with the conductor between the ends of which the voltage is required. Figs. 204, 205, etc., illustrate the proper connection for measuring the potential in the different parts of a circuit. *A voltmeter is never connected in series with the line* and an *ammeter never across or in parallel with the line*, but always in series with it, see Fig. 214. The following problems will illustrate the reason for each particular connection.

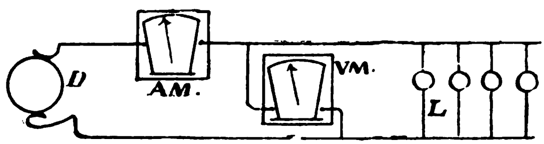


Fig. 214.—Connections of a Volt and Ammeter to a Circuit.

Prob. 95: In Fig. 214 the dynamo, D, maintains 110 volts across the mains at the lamps when 22 lamps are connected. Each lamp has a resistance of 220 ohms. What current will be indicated by the ammeter?

By Formula (43) $\text{J. R.} = \frac{R}{nq} = \frac{220}{22} = 10$ ohms.

By Formula (28) $I = \frac{E}{R} = \frac{110}{10} = 11$ amperes.

Prob. 96: Suppose the voltmeter, in Prob. 95, has a resistance of 110000 ohms and is incorrectly placed in series with the lamps. What current will the lamps receive, assuming the potential to be 110 volts?

By Formula (28) $I = \frac{E}{R} = \frac{110}{110000 + 10} = .0009$ ampere.

The lamps will not illuminate with this current since 10 amperes were required before.

Prob. 97: Suppose the above ammeter has a resistance of .1 ohm and is incorrectly connected across the circuit, like the voltmeter in Fig. 214, what current will it receive if the P. D. is 110 volts?

By Formula (28) $I = \frac{E}{R} = \frac{110}{.1} = 1100$ amperes.

Unless the ammeter had a current carrying capacity of 1100 amperes it would be destroyed by the excessive heat caused by such a large current.

237. Measuring High Voltages with a Low Range Instrument.—Suppose it is desired to measure the potential difference between a trolley line and the track which is about 550 volts, and only a 150 volt instrument is available. Connect five 110-volt lamps in series and to the track and line, and parallel the voltmeter with each lamp respectively. The sum of the voltages across each lamp equals the P. D. between the line and the track. In a similar manner other high voltages may be ascertained.

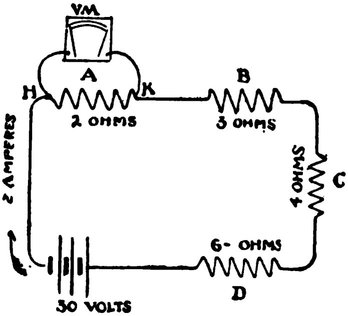


Fig. 215.—Measuring the "Volts Drop" with a Voltmeter.

238. Measurements with a Voltmeter.—

Exp. 65: Four spools of wire A, B, C, and D, Fig. 215, with resistances of 2, 3, 4, and 6 ohms respectively, are connected in series and to a battery. The spools may represent lamps, magnets, or

any other electrical devices. When the battery circuit is closed through the above circuit, and the voltmeter connected directly across its terminals, 30 volts potential difference is indicated. The total external resistance is $2 + 3 + 4 + 6 = 15$ ohms, and the 30 volts potential difference indicated by the voltmeter is the pressure causing the current to flow through this external resistance. The current is, by Formula (28) $30 \div 15 = 2$ amperes.

To measure the proportion of the total P. D., 30 volts, causing the current to pass through the 2 ohm spool, A, Fig. 215, the voltmeter is placed in parallel with it, or connected to the points H and K, and indicates 4 volts. When the voltmeter is connected across the 3 ohm spool B, 6 volts are indicated. The current is the same as through spool A, the resistance, however, being $1\frac{1}{2}$ times as great as A requires, also $1\frac{1}{2}$ times the voltage that A requires. Spool C has 4 ohms, or twice the resistance of A and the voltmeter indicates 8 volts.

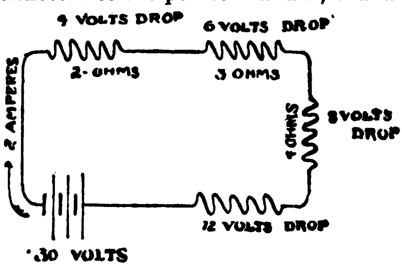


Fig. 216.—E. M. F. and Potential Difference in a Circuit.

By Formula (29) the voltage required to send 2 amperes through 4 ohms is calculated to be 8 volts, also in spool A the calculated voltage is $E = I \times R = 2 \times 2 = 4$ volts. The results of the measurements across the four spools by a voltmeter are indicated in Fig. 216, the sum of the volts drop on all the spools is $4 + 6 + 8 + 12 = 30$ volts or the potential difference measured at the battery. The total external resistance is 15 ohms, the current 2 amperes, and by Formula (29) the potential difference equals $I \times R = 15 \times 2 = 30$ volts. Suppose the internal resistance of the cells, r, is 5 ohms, then $E = I \times r$ or $2 \times 5 = 10$ volts drop in the cells. If the voltmeter is connected across the battery it indicates the P. D. 30 volts, when 2 amperes are flowing. If the external circuit is now opened the voltmeter indicates the E. M. F of the cells, which is the sum of all the former potential differences in the circuit or $30 + 10 = 40$ volts E. M. F. or the indication of the voltmeter now.

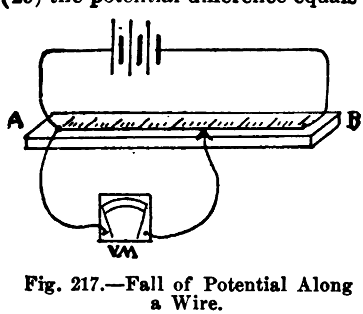


Fig. 217.—Fall of Potential Along a Wire.

Exp. 66.—In Fig. 217, a fine German silver wire, AB, uniform in size, is stretched on a board between binding posts and a scale of inches arranged directly above it. The wire is connected in circuit with one or more cells, preferably of the Daniell type, so that the current flowing through the wire will be constant. If the terminals of a

galvanometer or voltmeter are held on the wire, so as to include a portion of its length between them, as in Figure 217, the potential difference between the points embraced will be represented by the value of the deflection. One terminal may be fixed stationary at point A and the other terminal gradually moved along the wire toward B. The deflection increases as you proceed toward B. For example, with six inches between voltmeter terminals the drop is .4 volt; 12 inches, .8 volt, etc.

Since the current is the same in all parts of the circuit the same deflection will be produced for equal distances on the wire, provided its resistance is uniform. If a copper wire of the same size is connected in series with the German silver, the volts drop on 12 inches of copper will about equal the drop on 1 inch of German silver, since the latter has about twelve times the resistance of copper, and to send the same current through it, therefore, requires twelve times the pressure. The student should make a comparative table of lengths and deflections for several different wires of the same size joined in series, as the following:

Inches.	Copper	German Silver	Iron
	Deflections.	Deflections.	Deflections.
5			
10			
15			
Etc. . . .			

239. Volts Lost in Wiring Leads.—The size of wire required to conduct a given current a certain distance may be readily obtained by finding its resistance by Ohm's Law. In Fig. 218 a dynamo, D, is supplying current, 20 amperes, to a number of lamps,

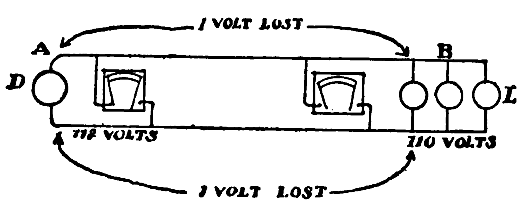


Fig. 218.—"Volts Lost" in Wiring Leads.

L, located at a distance of 100 feet. The potential at meter is 112 volts and at lamps 110 volts. There are thus 2 volts dropped on the line, or two volts are required to send 20

amperes through the 200 feet of copper wire. By Formula (30) the resistance of the line equals $E \div I = 2 \div 20 = .1$ ohm per 200 feet, or .5 ohm per 1000 feet. From the wire table, on p. 113, is found the nearest size of wire corresponding to .5 ohm per 1000 feet, which is a No. 7.

As a check upon this calculation the table of carrying capacities, ¶ 257, should be consulted to further ascertain whether the wire is large enough.

240. Comparison of E. M. F. of Cells by the Potentiometer.—The potentiometer is a simple instrument for measuring potential differences, or the E. M. F. of a cell. It consists of a fine German silver wire, AB, stretched between binding posts on a wooden base provided with a scale, Fig. 219. Current is passed through this wire in one direction, A to B, from several constant current cells, so that there is a constant P. D. between the ends of the wire, AB.

If this potential difference is known, the cell, the E. M. F. of which is to be determined, is connected in series with a galvanometer, and then in shunt with the potentiometer wire, so that its current will be in opposition to the potentiometer current. When the drop on the length of the potentiometer wire is equal and opposite to the cell's E. M. F. no current will flow through the galvanometer, and its needle will stand at the zero position. This point is determined by sliding the movable contact, C, along AB, till balance of the needle is obtained at zero. Then the E. M. F. of the cell bears the same relation to the P. D. between the ends of the potentiometer wire, AB, as the distance included between the cell terminals, AC, bears to the whole length of the potentiometer wire, AB.

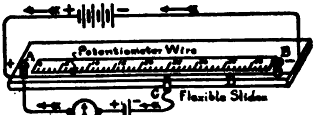


Fig. 219.—Connections of Potentiometer.

The potentiometer wire scale may be graduated to read in volts instead of inches. Thus 36 inches with 3 volts P. D. maintained would be 12 inches per volt. If the E. M. F. of one cell is known and used as a standard of E. M. F. the E. M. F. of any other cell may be determined from this standard.

The standard cell is first connected to the potentiometer wire, Fig. 219, and the distance, AC, on the scale divisions noted when balance is attained. The cell of unknown

E. M. F. is then substituted for the standard, being connected in opposition as before, and the distance AD noted when balance is obtained.

The following relation then exists when AC equals length on potentiometer wire balanced by the standard cell, and AD equals length balanced by the unknown cell:

$$\frac{\text{E. M. F. Standard}}{\text{E. M. F. Unknown}} = \frac{\text{Length AC}}{\text{Length AD}},$$

$$\text{Or unknown E. M. F.} = \frac{\text{E. M. F. Standard} \times \text{AD}}{\text{AC}} \quad (88).$$

When the potentiometer wire is graduated in volts, a voltmeter may be readily calibrated or re-calibrated, by substituting it for the cell and galvanometer, and noting the deflections on the voltmeter scale due to different potential differences applied by moving the flexible slider along the potentiometer wire.

Prob. 98: In a potentiometer test the standard cell, 1.05 volts E. M. F., produced a balance when 12 inches of the potentiometer wire were included between its terminals. What is the E. M. F. of two other cells measured if the potentiometer readings to produce balance were respectively 8 and 20 inches?

By Formula (88) Unknown E. M. F. =
$\frac{\text{E. M. F. Standard} \times \text{Length AD}}{\text{Length AC}} = \frac{1.05 \times 8}{12} = .7$ volt, E. M. F. of the first cell.

E. M. F. of Standard cell = 1.05 volts, AD = 8 inches, AC = 12 inches.

Also $\frac{1.05 \times 20}{12} = 1.75$ volts, E. M. F. of the second cell.

QUESTIONS.

1. The E. M. F. of a cell measured by a voltmeter is 1.8 volts. When connected to a spool of wire the voltmeter across the battery terminals indicates only .7 volt. Account for the volts lost, and state what pressure is applied to the spool.
2. Four coils of wire having resistances of 1000, 100, 10 and 1 ohms respectively are successively connected to a battery of 10 volts E. M. F. What will be the comparative value of the readings of a voltmeter placed across the terminals as compared with the E. M. F.? State also the comparative current strength in each case.
3. It is desired to measure the P. D. across a 250-volt power circuit, and only a voltmeter with a 100-volt scale is at hand. How would you make the measurement using this instrument?

4. The greater the current flowing through a voltmeter or ammeter the greater the deflection of its magnetic system. How then does a voltmeter measure electrical pressure?

5. In a potentiometer test balance of the galvanometer needle is attained with a standard cell of 1.05 volts for 210 divisions. For another cell the balance is attained at 430 divisions. What is the E. M. F. of the unknown cell? Give complete sketch.

6. What is the essential requirement in order to measure E. M. F. accurately, and how is it fulfilled in voltmeter construction?

7. Since the mechanical construction and resistance of the movable coil of a Weston voltmeter and ammeter are both the same, what then is the essential difference in the instruments?

8. Make a sketch of the internal connections of a Weston voltmeter.

9. What is a potentiometer, and for what is it used?

PROBLEMS.

1. Find the size of wire required to conduct current to 100 55-watt lamps in parallel, located at a distance of 125 feet from the dynamo, which maintains a constant pressure of 112 volts at its terminals. The lamps receive 110 volts. *Ans.* No. 2 B. & S.

2. What power is lost in the leads in question 1? *Ans.* 100 watts.

3. What P. D. must be maintained at the terminals of a dynamo so that 150 lamps, in parallel, each requiring 55 watts at 110 volts, will receive their proper current? Resistance of leads .02 ohm. *Ans.* 111.5 volts.

4. If the internal resistance of the armature in problem 3 is .05 ohm, what E. M. F. is developed by the machine? *Ans.* 115.25 volts.

5. How much resistance must be inserted in series with two 50-volt 50-watt lamps, to allow them to be placed in series across a 220 volt circuit? *Ans.* 120 ohms.

6. We desire to run a motor, requiring 1 ampere, at 6 volts from an Edison circuit of 110 volts potential difference. If two 50-volt 50-ohm (hot) incandescent lamps are connected in series with the motor, how much additional resistance must be added to meet the requirements? *Ans.* 4 ohms.

7. One hundred incandescent lamps, 110 volts 55 watts each, are to be installed in a private house. The distance from the meter to the general centre of distribution on the second floor is 150 feet. Potential at the meter is 113 volts and at the point of distribution 111 volts. Calculate the size and weight of wire required, using the two-wire direct current system. *Ans.* No. 1 B. & S., 73.5 or 76 lbs.

8. It is believed that the amount of power lost on a certain feeder in a central station is excessive. You are consulted and asked to determine the power so lost and the yearly cost of the same. The data furnished by the company is as follows: station runs 10 hours per day; the cost of producing an electrical horse-power-hour is 3.5 cents; the average daily load on this feeder is 100 amperes; the size of wire is No. 2. B. & S. gauge, and the distance to the point of distribution is 1000 feet; the system used is two-wire direct current. *Ans.* $555.74.

9. You are required to construct an electric heater for a trolley car, and find by experiment that 10 amperes flowing through a No. 16 B. & S. iron wire will radiate sufficient heat for the purpose. Assuming that the potential difference between trolley wire and track is 500 volts, find the length of wire required to properly place the stove in parallel with the circuit. (Neglect the rise in resistance due to the heat.) *Ans.* 2038 feet.

10. The two field magnets of a bipolar dynamo have a resistance of 55 ohms each, and are connected in series and placed in shunt with the brushes where 110 volts are maintained. (*a*) What is the field exciting current? (*b*) What is the total magnetising force, if the length of wire on each spool is 12,000 feet and the mean length of one turn 2 feet? (*c*) What will be the exciting current when the fields are placed in parallel with the brushes? *Ans.* (*a*) 1 ampere; (*b*) 12,000 A. T.; (*c*) 4 amperes.

11. (*a*) How much resistance would you insert in circuit with a 50 volt 50-watt incandescent lamp, to allow it to be properly placed across a 110-volt circuit? (*b*) How many feet of No. 18 B. & S. German silver wire are required to make a rheostat for this purpose? *Ans.* (*a*) 60 ohms; (*b*) 759 feet.

12. Four electromagnets having resistances of 4, 6, 8 and 10 ohms respectively, are connected in series and to a battery having an internal resistance of 2 ohms. When the switch is closed a voltmeter, across the battery terminals, indicates 56 volts. (*a*) What will be the indications of a voltmeter when paralleled with each spool? (*b*) What will the voltmeter indicate when placed across the cells when the magnets are disconnected? (*c*) What will be the efficiency of the battery when connected to the circuit? *Ans.* (*a*) 8, 12, 16 and 20 volts; (*b*) 60 volts; (*c*) 93 per cent.

13. What will be the drop on 500 feet of No. 0 wire used as an overhead trolley line at the instant when it is supplying current to four cars, each requiring 70 amperes? *Ans.* 14.2 volts.*

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* The student is advised to calculate resistances rather than take them from the wire table. Answers given for problems are based upon calculations from the formulæ given in this book.

LESSON XXI.

MEASUREMENT OF RESISTANCE.

Measurement of Resistance (Fall of Potential Method)—Measuring the Resistance of Arc and Incandescent Lamps While Burning—Measurement of Resistance (Substitution Method)—Drop Method of Comparison—Voltmeter Method—By Weston Instruments—Wheatstone Bridge (Principle of Slide Wire Pattern)—Lamp Chart Analogy of Wheatstone Bridge—Construction and Use of Slide Wire Bridge—Student's Wheatstone Bridge (Lozenge Pattern)—Operating the Bridge—To Measure a Higher Resistance Than That in the Rheostat—To Measure a Low Resistance—The Best Selection of Resistances for the Bridge Arms—Commercial Wheatstone Bridge—Direct Reading Ohmmeter—Questions and Problems.

241. Measurement of Resistance.—I. Fall of Potential Method (*Ammeter and voltmeter required*).—This is a very simple method for measuring an unknown resistance directly by Ohm's Law when an ammeter, a voltmeter and a source of current are available. Suppose the unknown resistance, A, Fig. 220, is the armature or field magnet of a dynamo. Connect the resistance to be measured in series with the ammeter and the source of electricity. Connect the voltmeter in parallel with, or across the resistance. Make simultaneous readings of both instruments. The unknown resistance is calculated from Formula (30) $R = E \div I$.

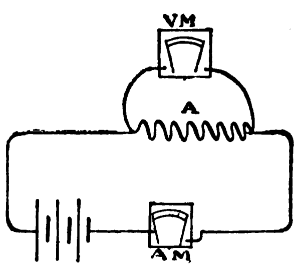

Fig. 220.--Fall of Potential Method for Measurement of Resistance.

In using this method precaution must be taken not to pass a greater current through the object to be measured than it will carry without heating, ¶ 257, otherwise a higher resistance than the true one will be measured. Generally the larger the current used, without heating, the greater the accuracy, because the voltmeter gives a higher reading. This

is especially true for measuring low resistances and for which this method is quite suitable. A milli-voltmeter will give greater accuracy when the resistance is quite low, as, for example, the series field of a large dynamo which may be .0001 ohm. On the other hand, when the method is applied to high resistances the current will be small and a milli-ammeter can be used to advantage.

Prob. 99: What is the resistance of the object A, Fig. 220, if the respective readings of ammeter and voltmeter are 4 and 36?

By Formula (30) $R = \frac{E}{I} = \frac{36}{4} = 9$ ohms.

$I = 4$ amperes, $E = 36$ volts.

Prob. 100: The resistance of a bonded rail is to be measured by the above method. The current through the rail and its copper joint is 500 amperes, the drop across the joint is 25 millivolts. What is the resistance in microhms?

By Formula (30) $R = \frac{E}{I} = \frac{.025}{500} = .00005$ ohm.
$E = 25$ millivolts $= .025$ volt, $I = 500$ amperes.

By Formula (12) $.00005 \times 1000000 = 50$ microhms.

242. Measuring the Resistance of Arc and Incandescent Lamps While Burning.—The fall of potential method, ¶ 241, is adapted to this measurement. Connections are shown for measuring an arc lamp while it is burning, in Fig. 221, and for measuring the hot resistance of one or more incandescent lamps while burning, in Fig. 214.

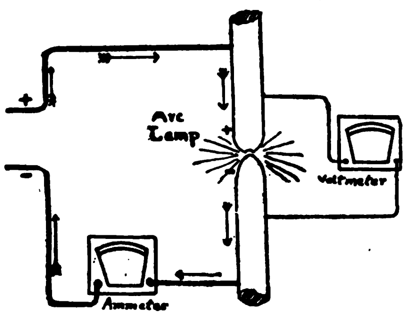

Fig. 221.—Measuring the Resistance of an Arc Lamp While it is Burning.

Suppose the pressure across the arc is 42 volts and the current 10 amperes, then the hot resistance is $42 \div 10 = 4.2$ ohms, Formula (30). This resistance is much less than when the carbon tips are in contact when the lamp is not burning. The resistance of carbon decreases with the temperature rise.

Prob. 101: A series arc-light dynamo is supplying a constant current of 10 amperes to a lamp circuit with a potential difference at the dynamo brushes of 2745 volts. Each lamp requires 45 volts and the resistance of the line is equal to the resistance of 1 lamp. (a) What is the resistance of the external circuit? (b) How many lamps are burning? (c) What is the resistance of 1 lamp? (d) How many lamps can be maintained by 1 electrical horse power? (e) How many electrical horse power are delivered by the dynamo? (f) What is the length of this series circuit if it is constructed of No. 6 B. & S. copper wire?

Solution: $2745 - 45 = 2700$ = volts drop on all the arc lamps.
45 = volts drop on the leads.

$$\frac{2700}{45} = 60 \text{ lamps burning (b).}$$

By Formula (30) $\frac{45}{10} = 4.5$ ohms resistance 1 lamp (c).

By Formula (30) $\frac{45}{10} = 4.5$ ohms resistance of line.

Total resistance $= (4.5 \times 60) + 4.5 = 274.5$ ohms (a).

By Formula (62) watts per lamp $= 45 \times 10 = 450$.

$$\frac{746}{450} = 1.65 \text{ lamps per H. P. (d).}$$

By Formula (65) $\text{H. P.} = \frac{E \times I}{746} = \frac{2745 \times 10}{746} = 36.79$ H. P. (e).

By Formula (23) $L = \frac{R \times C. M.}{K} = \frac{4.5 \times 26250}{10.79} = 10947.63$ feet (f).

No. 6 B. & S. = 26250 C. M.

243. Measurement of Resistance.—II. SUBSTITUTION METHOD (*Galvanometer and graduated rheostat required.*)—Connect the unknown resistance, X, and the galvanometer in series, and to one or more cells, preferably of the closed circuit type, as shown in Fig. 222. Note the deflection of the galvanometer needle. Now substitute the graduated rheostat for the unknown resistance and adjust it till the needle attains its former deflection.

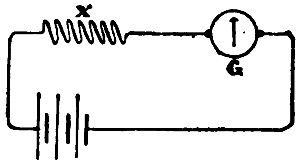

Fig. 222.—Substitution Method.

The resistance in the rheostat is now equal to the unknown resistance, since the current through the galvanometer is the same as before, and the pressure also the same.

If the unknown resistance is so small that the galvanometer needle is deflected off the scale, the rheostat may be inserted in series with the unknown resistance, and the resist-

ance unplugged till a suitable deflection is obtained. Then the unknown resistance is removed and resistance added by the rheostat till the deflection is the same as before; the resistance so added is equal to the unknown resistance.

Prob. 102: With the connections, as shown in Fig. 222, the deflection of the galvanometer with the unknown resistance in circuit was 25°. With the rheostat substituted it was found necessary to unplug 47 ohms to obtain a deflection of 25°. Therefore, 47 ohms is the resistance of the unknown object.

Prob. 103: When a small incandescent lamp was connected for cold resistance measurement, as in Fig. 222, the needle was deflected off the scale. The rheostat was inserted in series and 55 ohms unplugged when 40 deflections were indicated. The lamp is now removed and the deflections are 47. It required 12 ohms to be added to the circuit to reduce the deflections to 40, therefore 12 ohms is the cold resistance of the incandescent lamp.

244. Measurement of Resistance.—III. DROP METHOD OF COMPARISON (*A standard known resistance, or a graduated rheostat and a voltmeter required*).—This method is very convenient for many practical measurements. No ammeter is required. The known and unknown resistances are connected in series and to a source of constant current, Fig. 223. The drop across each resistance, as measured by the voltmeter, is directly proportional to that resistance, since the current is the same through both resistances. The drop on the known resistance also bears the same relation to the drop on the unknown resistance as the value of the known resistance bears to the value of the unknown resistance, or, calling the known resistance the standard and the unknown resistance X, then:

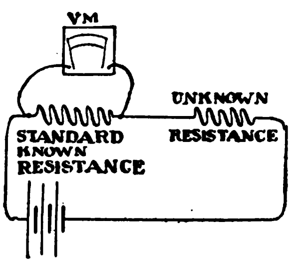

Fig. 223.—Measurement of Resistance by the Drop Method of Comparison.

$$\frac{\text{Drop on Standard}}{\text{Drop on X}} = \frac{\text{Resistance of Standard}}{\text{Resistance of X}}.$$

$$\text{Or unknown resistance X} = \frac{\text{Res. of Standard} \times \text{Drop on X}}{\text{Drop on Standard}} \quad (89).$$

A high resistance galvanometer, the deflections of which are proportional to the current, may be used instead of the voltmeter and the value of the deflections substituted in the

formula. In this method the current used should not be strong enough to heat the resistance appreciably. The most accurate results are obtained when the standard resistance is selected as near as possible to the supposed value of the unknown resistance. If the current is not very steady several readings should be taken of each measurement and the average value used in the formula. With suitable selected standards this method is adapted for measuring either high or low resistances with accuracy.

Prob. 104: With the connections as shown in Fig. 223, the drop on the standard resistance of 5 ohms was 2 volts, while the drop on the unknown resistance was 10 volts; the unknown resistance then is 5 times as great, or 25 ohms, or

By Formula (89) Resistance of $X = \frac{5 \times 10}{2} = 25$ ohms.

245. Measurement of Resistance.—IV. VOLTMETER METHOD (*Voltmeter of known resistance required*).—This method is especially adapted for measuring high resistances, as insulation of wires, etc. The voltmeter is connected directly across the source of E. M. F., which should be as high as possible, within the limits of the scale, and the deflection noted (which we will call d) by closing the switch K, Fig. 224. Switch K, is now open and the unknown resistance inserted in series with the voltmeter (call this deflection d_1), and the resistance of the voltmeter, r. The formula for finding the value of the unknown resistance R is

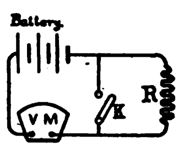

Fig. 224.—Measurement of Resistance by the Use of a Voltmeter.

$$R = r\left(\frac{d}{d_1} - 1\right) \quad \ldots\ldots\ldots\ldots\ (90).$$

Derivation of Formula (90).—Since the E. M. F. is constant, the drop through the voltmeter alone equals $C \times r$ which is also equal to the drop through the voltmeter and extra resistance or $C_1\ R + C_1\ r$. The deflection d or d_1, of the voltmeter needle is proportional to the current, therefore:

$$dr = d_1\ R + d_1\ r,$$

$$\text{transposing} \quad dr - d_1\ r = d_1\ R,$$

$$\text{dividing by } d_1 \quad \frac{dr}{d_1} - \frac{d_1\ r}{d_1} = R,$$

$$\text{or} \quad \frac{dr}{d_1} - r = R,$$

$$\text{or} \quad r\left(\frac{d}{d_1} - 1\right) = R.$$

Prob. 105: When the voltmeter in Fig. 224, is directly connected across the source of E. M. F. 110 volts are indicated; when placed in series with the unknown resistance, 4 volts are indicated, see Fig. 155. What is the value of the unknown resistance if the voltmeter has a resistance of 150000 ohms?

By Formula (90) $R = r\left(\frac{d}{d_1} - 1\right) =$

$150000\left(\frac{110}{4} - 1\right) = 150000 \times \left(\frac{110}{4} - \frac{4}{4}\right) =$

$$150000 \times \frac{106}{4} = 3{,}975{,}000 \text{ ohms, or } 3.975 \text{ megs.}$$

$d = 110$ volts, $d_1 = 4$ volts, $r = 150000$ ohms.

246. Measurement of Resistance.—V. By WESTON INSTRUMENTS.—A number of practical applications of the foregoing methods are illustrated in a catalog issued by the Weston Electrical Instrument Company.

247. Measurement of Resistance.—VI. WHEATSTONE BRIDGE (*Principle of the slide wire pattern*).—In Fig. 225 two unequal resistances, ab and cd, are connected in parallel and to a source of constant E. M. F. The drop across the wire, ab, is equal to the drop across the wire, cd, say 3 volts between points 1 and 2, the drop for any given length on ab is, however, not equal to the drop on the same length of cd, since the resistances are unequal. If some point as 3 is selected along ab, and the difference of potential between this point and a is 2 volts, then a corresponding point on cd can be found, as point 4, between which and c there will also be a difference of potential of 2 volts. This may readily be found by connecting one terminal of a galvanometer to point 3 and sliding the other terminal along cd until the galvanometer is not deflected when point 4 is found. Since there is no difference in potential then between points 3 and 4, no current flows through the galvanometer, consequently its needle remains at zero. If a piece of heavy wire were connected to points 3 and 4 under these conditions, no current would flow through it, nor would the current in the circuit be disturbed.

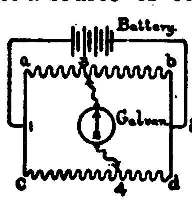

Fig. 225.—Principle of the Wheatstone Bridge.

If after a balance is so obtained the slider at 4 is moved nearer to c, the current divides at 3 and part flows to points 3 and 4 through the galvanometer, deflecting it to the right of zero, say, since the difference in pressure between c and 4

is less than 2 volts, while that between a and 3 is 2 volts. If, in the same manner, the slider at 4 is moved toward d, there is a greater drop across c–4 than a–3, and the current at 4 divides, part flowing to point 2 by 4–3 through the galvanometer, and deflecting its needle now in the opposite direction, or to the left. When the balance of the galvanometer needle is obtained the volts drop across a–3 is equal to the drop across c–4, and the drop across 3–b equal to the drop across 4–d. The value of the resistance a–3 bears the same ratio to that of c–4 as resistance 3–b compared with 4–d.

For example, if a–3 is 6 ohms and c–4 is 12 ohms, when a balance is obtained whatever is the resistance of 3–b, it will be just one-half as great as the resistance of 4–d. This relation enables any unknown resistance, such as 3–b, to be measured when the others are known, by balancing the potential differences in the divided circuit by moving the sliding contact 4 to the point of balance. From the proportion,

$$\frac{\text{Res. a–3}}{\text{Res. c–4}} = \frac{\text{Res. 3–b}}{\text{Res. 4–d}},$$

we get

$$\text{Res. 3–b} = \frac{\text{Res. a–3} \times \text{Res. 4–d}}{\text{Res. c–4}}.$$

When balance is obtained the values of the three resistances, a–3, c–4 and 4–d are substituted in the above formula and the unknown resistance, 3–b, is readily calculated.

248. Lamp Chart Analogy of Wheatstone Bridge.—

The balancing of potentials may be practically illustrated by a number of 16-C. P. 50-volt lamps (50 ohms hot), arranged as shown in Fig. 226 and connected to a dynamo circuit. Two lamps are connected in series at A, making the total resistance 100 ohms, which is connected in series with two lamps connected in parallel at C, the joint resistance of which is 25 ohms, Formula (43). The total resistance of A and C in series is, therefore, 125 ohms. If 125 volts are maintained across points 1 and 2, the circuit, AC, will receive one ampere, the drop

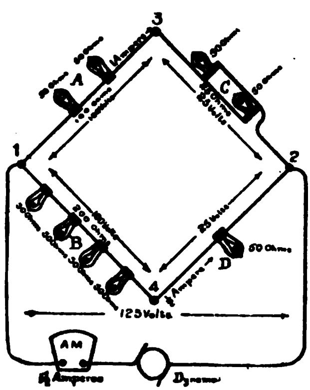

Fig. 226.—Lamp Chart Analogy of the Wheatstone Bridge.

across the lamps at A will be 100 volts and across the lamps at C, 25 volts. The A lamps burn at normal candle power, but the C lamps, dimly since they get only ½ ampere each.

Consider now the lower half of the circuit. At B, 4 lamps are connected in series so that resistance of B = 200 ohms, Formula (36) plus 1 lamp in series with them at D = 250 ohms for this lower circuit. The current therefore through B and D is one-half ampere, Formula (28), and all the lamps burn dimly since the drop across each lamp is only 125 ÷ 5 = 25 volts. The drop across B is therefore 100 volts, the same as it was across A, and 25 volts across D, or the same as across C. Now since the drop across 1–3 is exactly the same as that across 1–4, 100 volts, if points 3 and 4 are connected by a wire no current will flow through it and the lamps will burn with the same brilliancy as when 3 and 4 are not connected. If the resistance of the lamps is fairly uniform and a voltmeter is connected across 3 and 4 it will not show any appreciable deflection. If the wire across 3 and 4 is removed from 4 and placed, say to the right of the lamp at D,

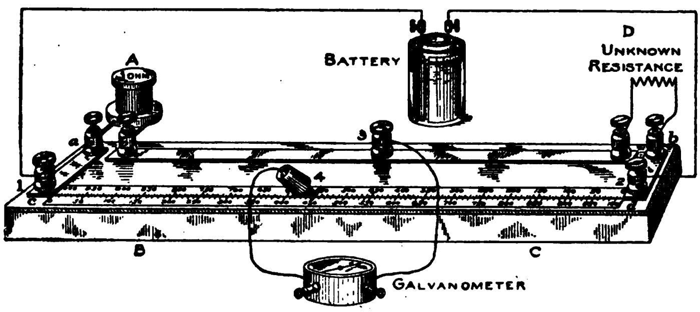

Fig. 227.—Student's Slide Wire Bridge.

Complete connections for measuring the unknown resistance at D are depicted. The student's Daniell cell and detector galvanometer are used.

then the condition of balance is destroyed, the lamps at A are subjected to 125 volts and burn above C. P. while lamps at C are cut out of circuit and the wire 3–4 carries the current flowing through the lamps at A.

This lamp chart should assist the student in understanding how the potentials are balanced in the slide wire bridge and the Wheatstone bridge, ¶ 250.

249. Construction and Use of Slide Wire Bridge.—A simple form of slide wire bridge for measuring resistance is depicted in Fig. 227. A piece of German silver or platinoid wire, about No. 24, is stretched between binding posts, cd, mounted on a wooden base. Directly under the wire is a paper double scale about 22 inches long, graduated in 1000 equal divisions with zero at either end, to facilitate taking readings from either point, c or d.

Strips of copper mounted on the base, support additional posts for reception of the spool resistance terminals and serve to make electrical connections. The small letters and figures indicate the same points on this bridge as shown in the diagram, Fig. 225, by which its principle was explained, ¶ 248. A resistance spool, with copper terminals, shown in detail in Fig. 228, and wound non-inductively, ¶ 299, is inserted in the binding posts at A, Fig. 227, and corresponds to the former resistance a–3. The unknown resistance, 3–b, is connected to the posts at D. The battery is connected across points 1 and 2, as before, and one galvanometer terminal to post 3, the other galvanometer post is connected to the flexible wire slider shown in detail in Fig. 228. The slider is moved along the wire, cd, till some point, as 4, is found where the needle is not deflected.

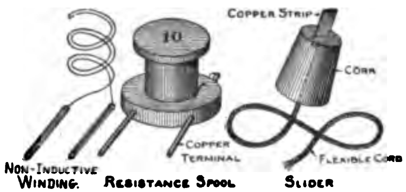

Fig. 228.—Details of Resistance Spool and Slider.

When balance is obtained the unknown resistance is calculated by the Formula in ¶ 248, as follows:

$$\text{Unknown Res.} = \frac{\text{Res. a-3} \times \text{length 4-d}}{\text{length c-4}}.$$

Referring to Figs. 227 and 229:

Let A = known resistance;
B = length of wire between c and point 4 when balance is obtained;
C = length of wire between point 4 and d when balance is obtained;
D = value of unknown resistance.

Then by the above formula,

$$\text{Resistance of D} = \frac{\text{Res. of A} \times \text{length C}}{\text{length B}} \quad \ldots\ldots\ldots\ldots \quad (91).$$

$$\text{More briefly } D = \frac{A \times C}{B}.$$

Several different spools are furnished with the bridge, such as 1, 10 and 100 ohms, and the proper spool to be inserted at point A, should be as near in value to the resistance to be measured as can be approximated before measurement. The error in measurement is less when this is the case.

The contacts should be clean and all wires fastened tightly, the slider should also be cleaned. Care must be exercised in moving the slider over the bridge wire so that it is not scraped, since the accuracy of measurement depends upon the uniform cross-section of the bridge wire. It is best to make several trial contacts at different points and note the direction of the needle's deflection, instead of running the slider along the wire. The same approximate pressure of the hand should be applied in making contact with the slider in different measurements. One or two cells in series will be sufficient for ordinary measurements and a switch can be introduced into this circuit to prevent the current from heating the wire, and also to prevent polarization, when open circuit cells are used. The slide wire bridge is adapted for measuring low resistances and is a laboratory instrument; the Wheatstone bridge, ¶ 250, is a commercial instrument for measuring high or low resistances.

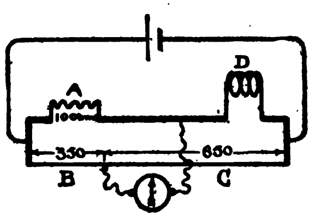

Fig. 229.—Slide Wire Bridge Connections.

Prob. 106: You are required to measure the resistance of a spool of wire which from rough calculation by Formula (22) is about 20 ohms. When inserted in the bridge the following data is recorded when balance is obtained: the 10 ohm spool was selected, B = 350 scale divisions read from the left-hand zero mark, C = 650 divisions read from right-hand zero mark. What is the value of the unknown resistance at D, Fig. 229?

By Formula (91) $D = \frac{A \times C}{B} = \frac{10 \times 650}{350} = 18.57$ ohms.

A = 10 ohms, C = 650 divisions, B = 350 divisions.

Prob. 107: In another measurement with the slide wire bridge, A = 100 ohms, B = 100 divisions, C = 900 divisions. What is the value of the unknown resistance?

By Formula (91) $D = \frac{A \times C}{B} = \frac{100 \times 900}{100} = 900$ ohms.

Prob. 108: What is the value of an unknown resistance measured by the slide wire bridge when A = 1 ohm, B = 900 divisions, C = 100 divisions.

By Formula (91) $D = \frac{A \times C}{B} = \frac{1 \times 100}{900} = .11$ ohm.

Problems 107 and 108 illustrate about the range of the bridge with the spools furnished, but the per cent of error in measurement increases as the resistance to be measured increases, and measurements are more accurate for low resistances with this type of bridge.

250. Student's Wheatstone Bridge (*Lozenge Pattern*).— The Wheatstone bridge is based upon the same principle of balancing potentials in a divided circuit as explained in ¶ 248.

In Fig. 230 a simple diagram of the circuit is given. A, B, C, and D are called the arms of the bridge. The unknown resistance is connected at D, a variable rheostat at C, and resistance spools are inserted in the arms, A and B. The connections and apparatus required for making measurements by the student's lozenge bridge are illustrated in Fig. 232. One of the spools of the resistance set, which was previously calculated by Formula (22) is inserted in the D arm for verification of the calculation by electrical measurement. The apparatus illustrated comprises the following parts: lozenge bridge with spools, student's Daniell cell, adjustable graduated rheostat, double contact key, and detector galvanometer. The arms are lettered to correspond with the diagram, Fig. 231.

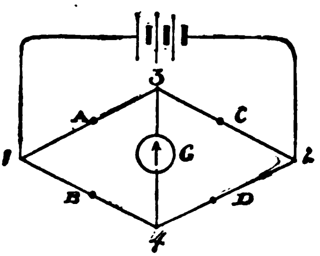

Fig. 230.—Principle of the Wheatstone Bridge.

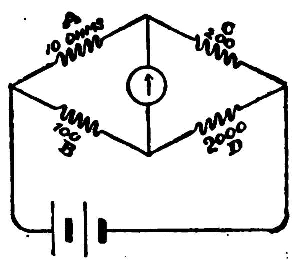

Fig. 231.—Principle of the Wheatstone Bridge.

The resistance in the arm, A, bears the same relation to that in B as the resistance in the rheostat at C does to the unknown resistance at D. Spools are selected for A and B and the resistance of C varied till the galvanometer needle stands at zero.

A balance of the resistances in the bridge arms is illustrated in Fig. 231. The proportion is shown by the values of the resistances in the arms which is as 10 is to 100, so is 200 to 2000, or

$$\frac{\text{Res. of A}}{\text{Res. of B}} = \frac{\text{Res. C}}{\text{Res. D}},$$

$$\text{Res. of D} = \frac{\text{Res. of B} \times \text{Res. of C}}{\text{Res. of A}},$$

$$\text{Res. of D} = \frac{B \times C}{A} \quad \ldots\ldots\ldots \quad \textbf{(92)}.$$

Six spools are provided with this particular bridge; 2 one-ohm, 2 ten-ohm, and 2 one-hundred-ohm spools. For the proper selection of spools see the following paragraphs.

The double contact key, **Fig. 232, is practically two button switches mounted on the same base, the upper switch connected to the two adjacent posts marked B, closes the battery circuit when a slight pressure is applied. The lower switch is connected to the other two posts**

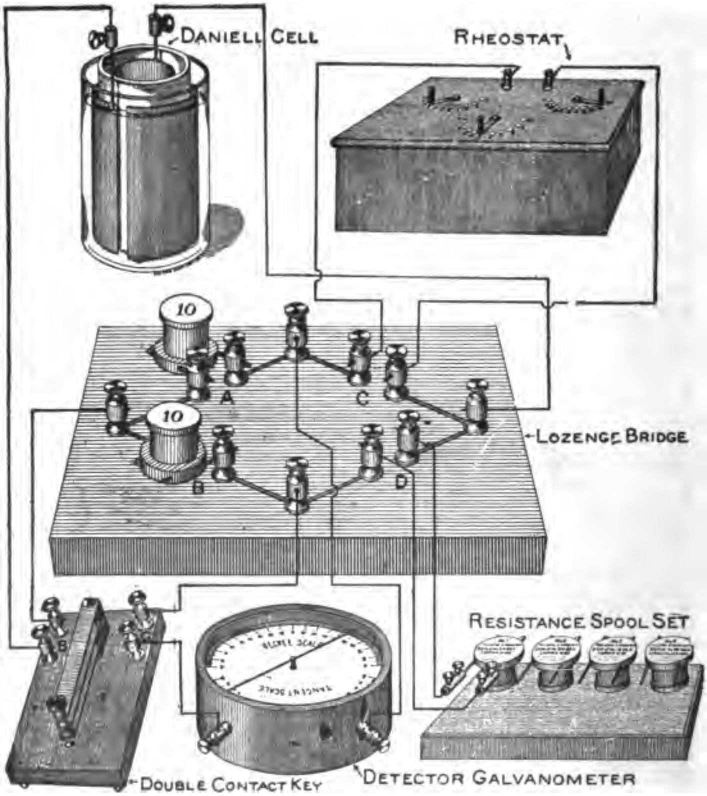

Fig. 232.—Student's Wheatstone Bridge (Lozenge Pattern) with the Necessary Apparatus Required for Measuring Resistance.
Connections should be made as depicted.

marked G, and is inserted in series with the galvanometer, Fig. 232. When the button is depressed two independent circuits are closed in this order. On breaking the circuits the galvanometer circuit breaks first. The battery circuit must always be closed before the galvanometer circuit in order to allow the current to become steady before closing the galvanometer key, hence the use of the double contact key.

251. Operating the Bridge.—Make the bridge connections as given in ¶ 250, and Fig. 232. Suppose the unknown resistance, a coil of wire connected at D, is about 20 ohms. Connect a 10 ohm spool in arms A and B. Connect the battery through the double contact key to posts marked B, likewise the galvanometer through the posts marked G. See that all connections are bright and tight. Insert resistance in the graduated rheostat to the value of what you suppose D will measure. Depress the double contact key and note *direction* of needle's deflection, say *to the left.* Release the key and add more resistance to the circuit by changing the position of the rheostat arm. If on depressing the key the deflection now is still *to the left but less than before,* release the key and *add more resistance.* If on the next trial the needle swings *to the right, too much resistance has been added* and some must be taken out of the rheostat circuit. Proceed in this manner till a balance is obtained. If on the first trial adding resistance had further increased the needle's deflection, too much had been taken out at the start. In the above case the needle swinging to the *right of zero* means that the rheostat's resistance *must be decreased* while the needle swinging to the *left of zero* indicates *too low a resistance* in the rheostat.

With the same pole of the battery always connected to the same bridge post, this relation of the needle's deflection will always hold good, and in such a case could be marked on the instrument, as is done in the portable bridge sets. Suppose a balance is obtained when 18 ohms are in the rheostat circuit.

Then by Formula (92) $D = \frac{B \times C}{A} = \frac{10 \times 18}{10} = 18$ ohms.

When the A and B arms have equal resistances they will always cancel in Formula (92), so that the unknown resistance is then equal to the amount inserted in the rheostat circuit, and can be read directly from it without reference to the formula. With equal resistances in the A and B arms, which should always be as near as possible to the unknown resistance, the maximum resistance that the bridge will

measure is limited to the resistance contained in the rheostat which, in the student's rheostat, illustrated in Fig. 232, is 160 ohms.

252. To Measure a Higher Resistance Than That in the Rheostat.—By inspection of Formula (92) Res. of $D = \frac{B \times C}{A}$ it will be observed that the value of resistance in the A arm is the divisor, so that if a low resistance spool is selected for it and a high resistance spool for the arm, B, the quotient will be high. For example, let $B = 100$ ohms, $A = 1$ ohm, and suppose that balance against some unknown resistance was obtained when 150 ohms had been inserted in the rheostat, then

$$D = \frac{100 \times 150}{1} = 15000 \text{ ohms},$$

or the bridge is capable of measuring a much higher resistance than that contained in the rheostat.

253. To Measure a Low Resistance.—

In this case the divisor A, in Formula (92) should be very large and B small, hence select spools for arms A and B accordingly. For example, let arm $B = 10$ ohms, and $A = 100$ ohms and balance obtained against some unknown resistance when 2 ohms were inserted in the rheostat, then

$$D = \frac{B \times C}{A} = \frac{10 \times 2}{100} = \frac{20}{100} = .2 \text{ ohm},$$

or the bridge will measure a much lower resistance than any contained in the rheostat. Suppose a balance is obtained in another measurement when $B = 1$, $A = 100$ and $C = 2$,

then, $$D = \frac{B \times C}{A} = \frac{1 \times 2}{100} = \frac{2}{100} = .02 \text{ ohm}.$$

254. The Best Selection of Resistances for the Bridge Arms.—The best selection of spools for the greatest accuracy in measurement depends upon the resistance of the galvanometer and the internal resistance and E. M. F. of the cells used with the bridge, so that no specific rule can be given beyond the varying of the ratios, as in ¶¶ 252 and 253.

255. Commercial Wheatstone Bridge.—The student's bridge, illustrated in Fig. 232, is a laboratory form for teaching the principles involved. A portable commercial bridge is shown in Fig. 233. The case contains the rheostat, bridge switch, and galvanometer. The unknown resistance to be measured is connected to the left-hand binding posts and the

battery to the right-hand pair of posts. In many portable bridges the battery is also contained within the case. Resistance is inserted in the arms by removing the plugs, as shown in detail in Fig. 235. A general plan of the portable bridge and its connections is depicted in Fig. 234. The letters and figures correspond to the previous diagrams, so that the lozenge may be traced out, though the parts are not arranged in the form of a lozenge. The A and B arms are provided with three different resistances, as in the student's type, which can here be used separately or all in series. The current divides at point 1 and unites again at point 2, and the galvanometer is placed across points 3 and 4, as in Fig. 230. The lozenge principle of Fig. 234 is further shown in detail in Fig. 235.

Fig. 233.—Portable Wheatstone Bridge Set (Commercial Type). The galvanometer and rheostat are contained in this case.

In using this type of bridge particular care must be observed to have the plugs tight, by giving them a slight twist to the right while inserting them. The galvanometer is delicate and the key should be tapped, rather than held down, so as to note the direction of deflection. This prevents the needle from being violently deflected when the system is not balanced. When a balance is nearly obtained the key may be held down for a longer time. For accurate measurements the current should not pass through the spools for any length of time, since their heating and consequent change in resistance is thus avoided. The choice of resist-

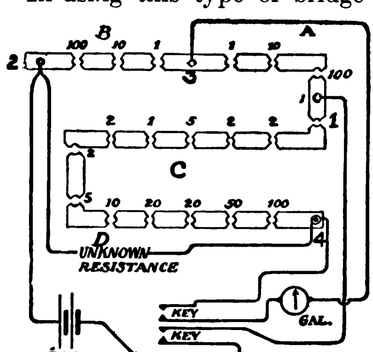

Fig. 234.—Arrangement and Connections of the Portable Wheatstone Bridge Set.

ance arms and method of operating are as given heretofore For measuring low and medium resistances one or two cells in series may suffice to operate the bridge. The higher the E. M. F. used the more accurate the results. For very high resistances, insulation resistance, etc., a number of cells, generally mounted in a separate case, ¶ 92, are employed.

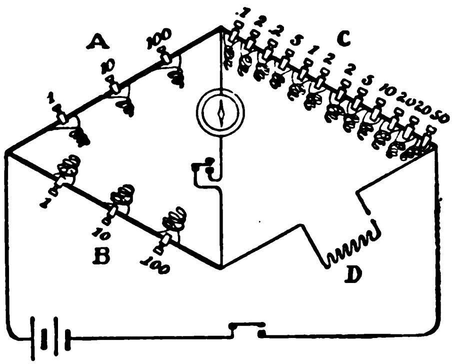

Fig. 235.—The Lozenge Diagram Applied to the Portable Wheatstone Bridge.

256. Direct Reading Ohmmeter.—This instrument measures automatically the resistance of any device that may be connected to its terminals. The resistance can be directly read from the dial of the instrument when the battery circuit is closed. An ohmmeter indicates the relation existing between the potential difference at the ends of a conductor and the current flowing through it, since the resistance in ohms is the ratio of volts ÷ amperes, Formula (30). The principle of action is as follows: Two coils, A, A, Fig. 236, are connected in series and to the source of current used in making the measurement, generally several cells for low resistance and a magneto, ¶ 322, for high resistance. Between these coils is suspended between jewel bearings a movable coil, B, at an angle to the coils A. A. The movable coil and resistance to be measured are connected in series and in shunt with the stationary coils A, A. This connection is made by joining the unknown resistance to the binding posts 1-2 Current is led to the movable coil by the springs, S, as in the case of the Weston movable coil, Fig. 198.

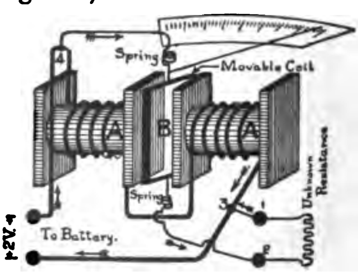

Fig. 236.—Construction and Connections of a Direct Reading Ohmmeter.

When the instrument is connected to the unknown resistance the current divides at point 4 in proportion to the resistances of the two circuits, and since the axes of the coils are at an angle, the movable coil tends to turn against the action of the springs so that its lines of force are in the same direction as the lines of force of the stationary coils. A pointer fixed to the movable coil swings over a scale graduated in ohms. With a low resistance connected to the instrument, the field of the movable coil is strong and that of the stationary coil weak, since the current divides between the two paths in proportion to the resistance. As the external resistance to be measured becomes higher, thus decreasing the current through the movable coil, the field of the stationary coil becomes stronger, so that the movable coil continues to be deflected and a very uniform scale is obtained. By using two sets of independent windings on the stationary coils, the instrument may be constructed with a double scale. The external appearance of the Weston portable ohmmeter is similar to that of the Weston voltmeter, Fig. 212, except that the push button is omitted and there are four or more binding posts. In one size of double scale instrument the capacity is 0 to 50 and 50 to 100 ohms, in one ohm divisions, and the instrument is to be used with an E. M. F. of 2 volts. For measuring high resistances, as the insulation of wires, a magneto-generator is used, capable of generating several hundred volts, and the scale of the ohmmeter graduated in megohms.

In some types of ohmmeters the magneto is mounted in the case with the instrument. When the value of the unknown resistance is not desired a magneto machine ¶ 322, is often used to test for insulation. The E. M. F. is several hundred volts but the current it will give is very small on account of its high internal resistance. A magneto is rated according to the value of the resistance its E. M. F. can maintain sufficient current through to ring a bell in series with it. For example, a 20000-ohm magneto means that if the *insulation* being tested *is less* than 20000 ohms, the bell will ring, thus indicating the fact. The higher the rating of a magneto the greater will be its E. M. F.

QUESTIONS.

1. What is the fundamental principle in the working of the Wheatstone bridge?

2. The highest and lowest resistances in the rheostat of a Wheatstone bridge are 10000 and .1 ohms respectively. The A and B arms have each 1, 10, and 100 ohm coils. What are the highest and lowest resistances the bridge is capable of measuring?

3. Make complete sketch of a slide wire bridge connected up to measure the resistance of 10 pounds of No. 10 B. & S. copper wire.

4. How does an ohmmeter differ from a Wheatstone bridge? Upon what principle does it operate? Make sketch.

5. One terminal of a magneto is connected to an electric light wire and the other to the ground. When the armature is revolved the bell fails to ring. What does this indicate?

PROBLEMS.

1. The drop across the series field coil of a dynamo carrying 250 amperes is .7 volt. What is its resistance? *Ans.* .0028 ohm.

2. A rheostat, battery, galvanometer and unknown resistance are joined in series. With 40 ohms unplugged the deflections are 33. The unknown resistance is cut out of circuit and 45 additional ohms are inserted to reduce the deflection to its former value. What is the value of the unknown resistance? Give sketch. *Ans.* 45 ohms.

3. You are required to measure the insulation resistance of an electromagnet using a proportionate deflection detector galvanometer, sensibility .00001 ampere for one degree and a 250 volt power circuit. The needle is deflected 3 degrees. What is the insulation resistance? Give sketch. *Ans.* 8,333,333 ohms or 8.3 megs.

4. The field magnets of a dynamo having a resistance of 84 ohms are connected in series with the field magnets of another machine and a current sent through the circuit. The drop on the latter field coils is 111 volts, and on the 84-ohm coils, 37 volts. What is the resistance of the second set of field magnets? Give sketch. *Ans.* 252 ohms.

5. An insulation test of a 110-volt multiple circuit is made with a Weston voltmeter (resistance 150000 ohms). The voltmeter indications are: positive to earth, 2 volts; negative to earth, 5 volts. What is the insulation resistance of each lead? Give sketch. *Ans.* Positive, 8.1 megs; negative, 3.15 megs.

6. Balance is obtained in a Wheatstone bridge when A = 10 ohms; B = 100 ohms; rheostat 14 ohms. What is the value of the unknown resistance? Give sketch. *Ans.* 140 ohms.

LESSON XXII.

ELECTRICAL DEVELOPMENT OF HEAT.

257. Heating of Conductors and Their Safe Carrying Capacity.—Heat is caused by the molecules of a body being set in motion. To produce this motion the expenditure of a definite amount of mechanical energy is required. When a current of electricity passes through a wire, a certain amount of work is performed in overcoming the resistance of the wire, and this work appears as heat generated, according to the principle of conservation of energy, ¶ 219. This fact becomes very noticeable when the wire is small and the current large; the wire may then become so hot that it is melted by the current, ¶ 97. The increase in the temperature of a wire due to the current, depends upon its weight or sectional area. For example, consider two copper wires, one weighing one pound, and the other twice as long but weighing four pounds, offering, therefore *equal resistance* to a current passed through them. The wires will not be raised to the same temperature, although the amount of heat evolved in each case is exactly the same. This is true because there is more metal to heat in one case than in the other. Thin wires, therefore, heat much more rapidly than thick ones of a like resistance when traversed by the same current. Since the resistance of metals increases as their temperature rises, a thin wire will have its resistance increased as it becomes heated, and will continue to grow warmer and warmer until its rate of loss of heat by conductance and convection to the surrounding air equals the rate at which the heat is evolved by the current.

Exp. 67: When a chain made of alternate links of platinum and silver wire of the same size, is connected to several cells joined in series, the platinum links become red-hot but the silver links remain comparatively cool. The resistance of platinum is about 6 times as great as silver, but its capacity to absorb heat only about one-half as great, hence its rise in temperature is about twelve times as great as that of the silver for the same current.

The rise in the temperature of a bare wire in air is usually greater than that of the same wire covered with insulating materials. The effect of the latter is to increase the surface from which the heat is radiated and carried away by convection. Wood being a very poor conductor radiates little heat, so that less current should be allowed for wires in wooden mouldings. The heating of a wire by a current is not objectionable except that it increases the loss of energy by the rise in resistance. The real limit of the current carrying capacity of a wire is at such a rise of temperature that the insulation is liable to be damaged. The National Electrical Code of the Fire Underwriters allows an elevation of temperature above the surrounding air of 27° to 30° F. for rubber covered wires used in carrying electric current. Figures are given in the following table for this elevation. The current can be increased nearly 60 per cent above these conservative figures without any injurious effect. Wires with "weatherproof" insulation will carry still more current, since they are not so readily affected by heat.

Table XV.—Current Carrying Capacity of Copper Wires

B. & S.	Amperes.	B. & S.	Amperes.
18	3	4	65
16	6	3	76
14	12	2	90
12	17	1	107
10	24	0	127
8	33	00	150
6	46	000	177
5	54	0000	210

The carrying capacity of copper wires used in dynamos varies from 600 to 1000 circular mils per ampere, according to the amount of ventilation the wire may receive. A much larger allowance must be made for contact surfaces in a

circuit, as between the brushes of a dynamo and the commutator, the clips of a switch, etc.; about 100 amperes per square inch of contact surface is an average value. Switches are constructed and rated according to their carrying capacities.

258. Electrical Development of Heat.—I. HEAT DEVELOPED IS DIRECTLY PROPORTIONAL TO THE RESISTANCE OF THE CIRCUIT.—In Fig. 237 two independent glass bulbs are connected with a graduated glass U tube and fastened to a suitable base by the vertical brass arm, B–2. Platinum wires are inserted in each bulb through a cork and connected to the binding posts, 1, 2, 3, as shown, post 2 being a common terminal for the wires in both bulbs. Suppose the wire, BC, in the right-hand bulb is exactly *double the length* of the wire in the left-hand bulb, but of the *same size.* Partially fill the graduated U tubes with water, close the stop-cocks and connect several cells in series to posts 1 and 3, when both platinum wires will be in series and the current the same through each of them. Permit the current to flow for a short time. The column of water in the open side of the right-hand U tube rises to about double the height above the normal position that the column in the left-hand tube does. *A gas under constant pressure expands by a definite fraction of its volume for a given increase of temperature,* consequently the air in the bulb, BC, must have been raised to double the temperature of that in the bulb, AB, or double the quantity of heat must have been evolved from the wire of twice the length, by the current. *The heat generated in any wire is directly proportional to its resistance.* In a cell furnishing current to an external circuit, twice the heat is evolved from the inside of the cell, if the plates are separated to twice their original distance and the current the same in both cases.

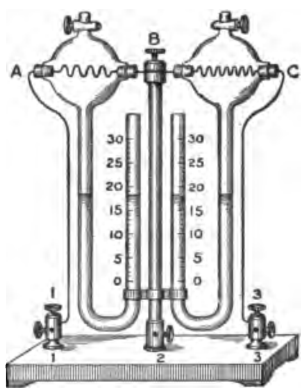

Fig. 237.—Apparatus for Studying the Laws Governing the Heating Effect of an Electric Current.

2. **Heat Developed is Proportional to the Square of the Current.**—To prove this statement, connect an ammeter in series with either of the bulbs in Fig. 237 by using two adjacent posts, 1–2 or 2–3. Note the value of the current in amperes, and the corresponding number of cubic centimeters rise of the level of the liquid in the U tube in a given time. Now double the current strength, and the liquid in the U tube rises, not to twice the former height, but to *four* times the former height in the *same* time. If the current is tripled the liquid rises to nine times the height recorded in the first test, and when quadrupled to sixteen times the first height, etc. For example, one ampere produces 3 divisions rise; 2 amperes produce 12 divisions rise ($(2 \times 2) \times 3$); 3 amperes produce 27 divisions rise ($(3 \times 3) \times 3$), all tests being run for the same length of time. The heat developed is directly proportional to the square of the current.

3. **Heat Developed is Directly Proportional to the Time.**—This statement is so apparent that it need not be further considered.

259. Electrical Equivalent of Heat.—Joule's Law.—Dr. Joule first discovered that the development of heat was proportional to:

1. *The resistance of the conductor;*
2. *The square of the current;*
3. *The time during which the current flows.*

The heat (H) developed in a unit of time is directly proportional to the amount of power expended in overcoming the resistance of the conductor, or to the product of current C, through the conductor, and the difference of potential E between its extremities, or $H = E \times I$. If the resistance of the wire remains constant, the value of I varies directly as E, so that by doubling E, I will also be doubled or the heat developed will be proportional to the square of the current as experimentally demonstrated in ¶ 258. *The British Thermal Heat Unit (written B. T. U.) is defined as the amount of heat required to raise one pound of water 1° Fahrenheit (written 1° F.) at its maximum density.*

A P. D. of 1 volt maintained across a resistance of 1 ohm for one second develops .0009477 of such a unit. The number of heat units developed in any number of seconds therefore is,

Heat Units (H) $= .0009477 \times E \times I \times t$ . . . **(93).**

$t =$ the time in seconds. Substituting for E its value $I \times R$,

then $H = .0009477\ I^2 R\ t$ . . . . **(94).**

Also since $W = I^2 R$,

$H = .0009477 \times \text{watts} \times \text{seconds}$ . . . . **(95).**

TO FIND THE TOTAL HEAT UNITS DEVELOPED IN A GIVEN TIME IN ANY CIRCUIT:

Multiply the watts expended by the time the current flows and this product by .0009477, as in Formula (95). Formula (94) will give the same result.*

Prob. 109.—How many heat units are evolved in one-half hour by a 110-volt incandescent lamp consuming a current of ½ ampere?

By Formula (93) $H = .0009477 \times E \times I \times t =$
$.0009477 \times 110 \times .5 \times 1800 = 93.8223$ heat units.
$E = 110$ volts, $I = \frac{1}{2}$ ampere, $t = \frac{1}{2}$-hour $= 1800$ seconds

TO FIND THE CURRENT REQUIRED TO PRODUCE ANY GIVEN NUMBER OF HEAT UNITS BY A KNOWN E. M. F. IN A GIVEN TIME:

Use the following formulæ derived directly by transposition from Formula (93):

$$I = \frac{H}{.0009477 \times E \times t} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ \textbf{(96).}$$

$$t = \frac{H}{.0009477 \times E \times I} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ \textbf{(97).}$$

Prob. 110: A 110-volt ½-ampere incandescent lamp is immersed in a vessel containing 1 pound of water. How long a time will be required to raise the water to the boiling point? The temperature of the water before the test is 60° F. Neglect losses, due to radiation, etc., and assume that all the energy is converted into heat.

Solution: The water must be raised $212° - 60° = 152°$.
1 lb. $\times$ 152 = 152 heat units to be given to the water.

By Formula (97) $t = \frac{H}{.0009477 \times E \times I} = \frac{152}{.0009477 \times 110 \times .5} = 2916$ **sec.**

$\frac{2916}{60} = 48$ min. 36 sec. till water boils.

Prob. 111: What current will be required by a lamp immersed in the above pound of water to boil it in one-half hour? The E. M. F. is 110 volts; heat losses to be neglected.
Solution: Solve by Formula (96). *Ans.* 0.8 ampere.

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*If the Centigrade scale is used and the gramme unit employed, then Formula (93) becomes $H = .24\ E\ I\ t$, since .24 heat unit is evolved by one watt in one second. In this case the heat unit is called the *calorie, and is the amount of heat required to raise one gramme of water one degree.*

260. Relation Between Heat, Mechanical and Electrical Energy.—Referring to ¶ 217, Formula (60) etc., we find that the electrical work performed in a circuit is proportional to the same factors as the heat development, Formula (94). This is true, since the electrical work appears as heat. The following problem will illustrate the relation between electrical work, in joules, ¶ 217, and electrical heat, in heat units or B. T. U.

Prob. 112: A current of 4 amperes flows through 2 ohms for 3 seconds. (a) Find the work performed in joules. (b) Find the number of heat units developed in the circuit.

By Formula (60) $J = I^2R\,t = 4 \times 4 \times 2 \times 3 = 96$ joules (a).

By Formula (94) $H = .0009477\ I^2R\,t = .0009477 \times 4 \times 4 \times 2 \times 3 =$ .0909792 heat unit.

Therefore 96 joules = .0909792 heat unit;
1 joule = .0009477 heat unit.

The relation between mechanical energy, electrical energy and heat energy, ¶ 220, is then as follows:

Mechanical Energy—Electrical Energy—
778 foot-pounds = 1055 joules =
Heat Energy.
1 B. T. U.

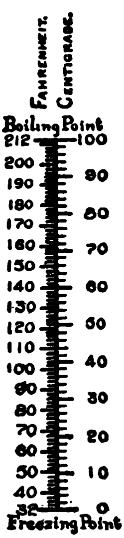

Fig. 238.—Comparison of Fahrenheit and Centigrade Thermometer Scales.

261. Relation of Fahrenheit and Centigrade Thermometer Scales.—Since both of these scales are much used in referring to the resistance of a wire at a particular temperature, the relation between them is given by the formulæ below, and also shown diagramatically by Fig. 238. On the Fahrenheit scale the melting point of ice is placed at 32° and the boiling point at 212°, while on the Centigrade scale the melting point of ice is placed at zero and the boiling point at 100°. Therefore 100° C. = 212 — 32 = 180° F. or the ratio of C.° to F.° is as 5 to 9. In converting a Centigrade reading into a Fahrenheit reading 32 must be added, since the zero is 32° below Centigrade, and conversely 32 must be subtracted from a Fahrenheit reading.

1. To Convert Fahrenheit to Centigrade: *Subtract 32, multiply by 5 and divide by 9.*

$$C^\circ = \frac{(F^\circ - 32)\,5}{9} \quad \ldots\ldots\ldots\ldots\ldots \quad (98).$$

2. TO CONVERT CENTIGRADE TO FAHRENHEIT: *Multiply by 9, divide by 5 and add 32.*

$$F^\circ = \frac{C^\circ \times 9}{5} + 32 \ldots\ldots\ldots\ldots \quad \textbf{(99)}.$$

Prob. 113: A field magnet spool is stated to have a resistance of 25 ohms at 15.5° C. Express this temperature in degrees Fahrenheit.

By Formula (99) $F^\circ = \frac{C^\circ \times 9}{5} + 32 = \frac{15.5 \times 9}{5} + 32 = 59.9$ or nearly 60° F.

Prob. 114: The resistance of a unit foot of copper wire was stated to be 10.79 ohms at 75° F. What is the corresponding temperature in the Centigrade scale?

By Formula (98) $C^\circ = \frac{(F^\circ - 32)\ 5}{9} = \frac{(75 - 32) \times 5}{9} = 24^\circ$ C nearly.

262. Relation of Resistance to Temperature.—Refer to Law V of the Laws of Resistance, ¶ 127, for the relation of temperature to resistance of wires. The *proportional* change in resistance of a wire with a unit change in temperature is known as the *temperature coefficient.* For example, the resistance of 1000 feet of wire one-tenth inch in diameter is about 1 ohm at 76° F., Fig. 102, and at 100° F. the resistance is increased to 1.0525, while at 50° F. the resistance is only .9475 of an ohm. This change in the resistance of a wire due to the temperature rise or fall is a very important matter in electrical calculations and measurements, and must always be taken into consideration. The following formulæ and temperature coefficients will enable the student to calculate the resistance of different metals at different temperatures:

Let R = the original resistance;
R_1 = the resistance after a rise or fall in temperature;
F° = number of degrees rise or fall;
T = the temperature coefficient for Fahrenheit scale or the change per degree per ohm.

The formula for finding the increase in resistance due to a rise in temperature is:

$$R_1 = R\,[1 + (T \times F^\circ \text{ Rise})] \ldots\ldots \quad \textbf{(100)}.$$

And the formula for a fall in temperature is:

$$R_1 = R\,[1 - (T \times F^\circ \text{ Fall})] \ldots\ldots \quad \textbf{(101)}.$$

When the Centigrade scale is used select the temperature coefficient (T) for this scale and substitute C° for F° in the above formulæ. The following temperature coefficients (values of

T) are given for some metals. The figures represent the amount 1 ohm would increase or decrease in resistance when subjected to a rise or fall of so many degrees F. or C. For example, 1 ohm of copper wire for a rise of 1° F. has a resistance of 1.0024; 10 ohms for 1° = 10.024; or 10 ohms for 10° = 10.24 by Formula (100).

Table XVI.—Temperature Coefficients.

Metal.	Values of T.	
	Fahrenheit Scale.	Centigrade Scale.
Silver	.00222	.00400
Copper (annealed)	.00242	.00428
Aluminum (99%)	.00235	.00423
Platinum	.00137	.00247
Iron	.00347	.00625
Tin	.00245	.00440
Lead	.00228	.00411
Bismuth	.00197	.00354
Mercury	.00044	.00072
German Silver (average)	.00019	.00033

The resistance of copper wire thus increases nearly one-quarter of 1 per cent. (.0024) for each degree F. for each ohm, and iron wire more than one-third of 1 per cent. (.00347).

Prob. 115: The resistance of the field magnets of dynamo is 55 ohms at 70° F.; after a ten-hour run the temperature of a thermometer placed against them, for a short time, is 94°. (a) What is their resistance at this temperature? (b) What would be the resistance at 40° F.?

By Formula (100) $R_1 = R\,[1 + (T \times F^\circ \text{ rise})] = 55\,[1 + (.00242 \times 24)] = 58.194$ ohms (a).
$R = 55$ ohms, T for copper wire $= .00242$, $F.^\circ = 94^\circ - 70^\circ = 24^\circ$ rise.
By Formula (101) $R_1 = R\,[1 - (T \times F^\circ \text{ fall})] = 55\,[1 - (.00242 \times 30)] = 51.007$ ohms (b).
$R = 55$ ohms, $T = .00242$, $F^\circ = 70^\circ - 40^\circ = 30^\circ$ fall.

263. Fuses and Cut-Outs.—When a piece of copper and lead wire of the same size are connected in series and a current passed through them so that their temperature is increased, the lead will melt when a temperature of 612° F. is attained, while

it will require a temperature of 1996° F. to melt the copper. Lead containing a small percentage of tin is used for electric fuses on account of the low temperature at which it melts. A fuse consists of such a leaden wire or strip which is inserted in series with the circuit it is desired to protect, and designed so as to melt, and thus automatically open the circuit when the current through it becomes excessive. The fuse is mounted on a porcelain block and the appliance termed a cut-out. The carrying capacity of a fuse depends upon its cross-section, and fuse wire is generally rated to be of so many amperes capacity, meaning that it will carry this current without melting or "blowing," as it is termed, and melt on a slight increase in current above its capacity. The function of a fuse, therefore, is to open the circuit before the temperature rise due to an excessive current from any cause, has opportunity to heat the conductors. A circuit breaker, Fig. 176, performs the same function. The gauges of different wires fused by a current of 100 amperes, is given in the following table:

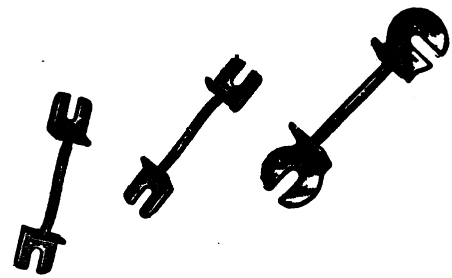

Fig. 239.—Copper Tipped Link Fuses for Cut-Outs.

Table XVII.—Gauges of Different Wires Fused by 100 Amperes (Preece).

Copper	No. 17 B. & S.	Iron	No. 10 B. & S.
Aluminum	15 "	Tin	6 "
Platinum	13 "	Lead	6 "
German Silver	13 "	Tin Alloy	5 "
Platinoid	12 "		

264. Electric Cautery, Blasting, Welding and Cooking. In surgery a thin platinum wire heated to a white heat by the current is used for many operations instead of a knife.

Platinum is chosen because it is the most refractory metal but is readily fused when the current is too strong.

In blasting, the fuse is surrounded by some combustible material in proximity to the explosive. A current sent from a distant battery, through copper wires, melts the fuse or heats the platinum wire, as the case may be, and the combustible is ignited and the powder exploded.

In electric welding the terminals of the parts to be joined, form the electrodes of the source of supply, which is generally of a low voltage but capable of giving a large volume of current. When the circuit is completed at the electrodes most of the energy is expended at this junction, since it is of higher resistance than the other parts of the circuit, and appears as heat. The current in such operations is often obtained from transformers and may be several hundred amperes at a few volts pressure.

In the *water-pail system of welding* a direct current of about 200 volts is used and the metallic tank containing, for example, a solution of ordinary washing soda, is connected to the positive pole of the supply source. The tongs are connected to the negative pole and the piece to be heated clamped in them and immersed in the solution when it becomes heated to a welding heat. The heating is due to the film of hydrogen which collects around the negative pole (by electrolysis, ¶ 100) and greatly increases the resistance at that point. In welding, two pair of tongs connected to the negative pole may be used simultaneously.

In electric cooking utensils, iron or other high resistance wire is wound around some insulator of electricity, as a porcelain or asbestos tube, and these coils inserted in the utensil desired. The heat is radiated to some good heat conductor in the vicinity of the coils, as for example, the copper bottom or sides of an electric tea-kettle. The wire is proportioned so that it will contain sufficient resistance to be placed in multiple with an incandescent lamp circuit and permit enough current to flow through it to maintain a temperature somewhat below its fusing point. A good heat conductor, as copper, may be coated with some insulating enamel and the wire wound directly upon it. This method is used in some makes of rheostats, ¶ 163. The advantage is that the heat is radiated so rapidly that the wire will carry a much larger current than under other conditions.

QUESTIONS.

1. A cell is short-circuited by a thick piece of copper having a low resistance as compared with that of the cell; the current from the cell is a maximum. Where will the most heat be developed?

2. Cite an experiment to prove that heat developed in a circuit is proportional to the square of the current.

3. Equal lengths of No. 10 and No. 20 B. & S. copper wire are connected in series and to a cell. Is there any difference in the strength of current through, or heat evolved from, either wire?

4. A thermometer is immersed in a vessel containing dilute sulphuric acid and a plate of zinc and copper. When the extremities of the plates are connected by a wire the temperature rises. Explain this.

5. The size of wire for carrying 62 amperes with rubber covered insulation is calculated to be, in a certain instance, No. 6 B. & S. Would you use this size of wire? Why?

PROBLEMS.

1. How many heat units are evolved in 10 hours from an arc lamp requiring 10 amperes and 45 volts? *Ans.* 15352.74.

2. How many pounds of water can be raised from 80° Fahr. to boiling point by the heat evolved in Problem 1, neglecting all losses? *Ans.* 116.3 lbs.

3. With an E. M. F. of 110 volts what current must be passed through a coil of iron wire, immersed in 2 pounds of water so that it will boil in 45 minutes? The temperature of the water at the start is 60° Fahr. *Ans.* 1.08 amperes.

4. The hot resistance of an electrical laundry iron is 22 ohms and it is connected across a 110-volt main. Suppose the iron to be thrown into a vessel containing 4 quarts of water, the temperature of which is 60° Fahr., and the current turned on for 15 minutes. What will be the temperature of the water at the end of the time, not deducting losses for radiation, etc? *Ans.* 116.24° Fahr.

5. Give the equivalent amount of energy in joules and foot-pounds expended in the arc lamp in question 1. *Ans.* 16,200,000 joules; 11,947,500 foot-lbs., or 11,946,902 foot-lbs.

6. The length of the Institute concentric power cable, laid in ducts under Broad street, is 300 feet; the size of conductor, No. 4 B. & S.; suppose that the temperature in the ducts on a warm summer day is 104° Fahr., and during a blizzard in winter, 40° Fahr. (a) What will be the resistance of the cable in each case? (b) If the cable is delivering 30 Kilowatt at 1100 volts, what will be the lost power on the line, at the summer temperature as above? (c) What will be the cost of this loss, running 5 hours a day for 6 months (180 days) at 7½ cents per horse-power-hour? *Ans.* (a) .1658 ohm at 104° Fahr.; .1418 ohm at 40° Fahr.; (b) 123.297 watts; (c) $11.172.

LESSON XXIII.

ELECTRODYNAMICS.

Reaction of a Current-Carrying Wire on a Magnet—Automatic Twisting of a Current-Carrying Wire Around a Magnetic Pole—Rotation of a Current-Carrying Wire Around a Magnetic Pole—Electrodynamics—The Magnetic Fields of Parallel Currents—Laws of Parallel and Angular Currents—Currents in Angular Conductors—The Electro-Dynamometer—Portable Dynamometer Ammeter—Dynamometer Wattmeter—Thomson Recording Wattmeter—Questions.

265. Reaction of a Current-Carrying Wire on a Magnet.—Every action is accompanied by an equal and opposite reaction, or, "action and reaction are equal and opposite," ¶ 57. For example, you elongate a spring in one direction by applying a force of one pound; the spring also exerts an equal force in the opposite direction, or else it would break. A ship displaces an amount of water which is equal to its own weight, the force of buoyancy is therefore equal and opposite to the force exerted by the weight of the ship, or else it would sink. In Lesson XV it was shown how a magnet was deflected by the magnetic field of a wire carrying a current. When the current flows over the needle, say from **N** to **S**, and the needle is *free to move*, the **N**-end is urged by the current's field to the east and the **S**-end, to the west. Since the field of the wire repels the magnet's field the magnet's field also repels the field of the wire, and if it were free to move it would move in the opposite direction to that of the magnet. In ¶ 170 the right-hand rule was given for the direction in which the needle would turn, the following rule employing the left hand will indicate the direction that the wire will move when the magnet is stationary. *Arrange the wire over the needle and place the palm of the* LEFT HAND *over the wire as before, ¶ 170; the outstretched thumb at right angles to the hand will indicate the direction the wire will move.*

Exp. 68:—Insert the rectangular coil of a single turn of wire, Fig. 248, in the ampere frame, as shown in Fig. 240. Arrange the horizontal portion of the coil in the magnetic meridian, and by the use of

a pocket compass find the direction of current around the wire. Open the circuit and lay a bar magnet on the ampere frame base, arranged so that the current flows over it from **N** to **S**, as in Fig. 240. The magnet is now stationary and the wire free to move. When the current flows through the wire it is deflected west. Apply the left-hand rule, ¶ 265, to this case.

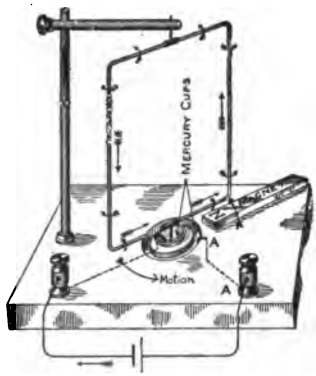

Fig. 240.—The Movable Current-Carrying Coil is Repelled by the Stationary Bar Magnet.

Exp. 69: Explore the magnetic field both inside and outside of the rectangular coil by noting how the wire moves when the magnet is brought into its vicinity. The wire tends to move in all cases to such a position that its own lines of force are in the same direction as those of the field of the magnet.

266. Automatic Twisting of a Current-Carrying Wire Around a Magnetic Pole.—That a wire tends to move so that its magnetic field will be in the same direction as the lines of force of the magnet's field is further demonstrated as follows : a bar magnet is clamped vertically in a stand and raised several inches from the table, Fig. 241, a connector is clamped above it, and a piece of tinsel wire, which is a very flexible conductor, is supported from the connector and connected to a battery as shown. When the current is sent up the wire from A to B, the wire twists or winds itself around the magnet in a left-hand spiral, that is, so that the current circulates around the magnet anti-clockwise as viewed from the **N**-pole end. The current, therefore, tends to increase the magnetism of the magnet and the lines of force of both are in the same direction. When the current is reversed, the tinsel unwinds and again twists itself around the magnet in a right-hand spiral, or so that the polarity at **N** is increased by the current's field as before.

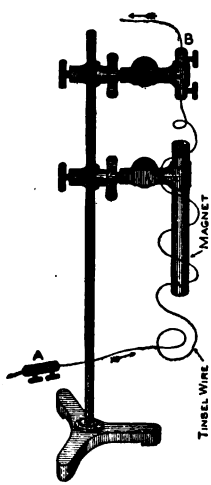

Fig. 241.—The Flexible Tinsel Wire Winds Around the Magnet when a Current is Sent Through it.

267. Rotation of a Current-Carrying Wire Around a Magnetic Pole.—Since the tendency of a magnet is to urge a wire carrying a current to a position at right angles to it, continuous rotation of the wire can be produced if the wire be arranged free to move and in such a manner that it will never attain such a position. In Fig. 242 a wooden ring with a groove turned in it for the reception of mercury is mounted above an electromagnet. One end of a piece of copper wire, AB, is hooked on to the stationary horizontal brass arm, which is supported by the vertical rod as depicted. The other end of the copper wire dips into the mercury trough and serves to complete the circuit of the battery current through the electromagnet.

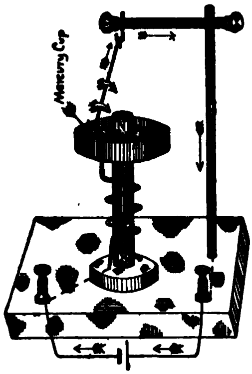

Fig. 242.—Rotation of a Current-Carrying Wire Around a Magnetic Pole.

The magnetic field of the electromagnet is nearly at right angles to the field of the wire, and the wire rotates about the pole, when the current is passed through it, according to the principle that *a magnetic body free to move, tends to move so that its lines of force will be in the same direction as the lines of the field in which it is placed.*

The direction of rotation can be determined before the current is turned on by the following *left-hand rule:*

Place the thumb, first and second fingers of the left hand all at right angles to each other, as in Fig. 243, and the hand so that the first finger indicates the direction of the lines of force of the magnet, and the second finger the direction of the current in the wire; the thumb will then indicate the direction of motion of the wire. Applying the left-hand rule to Fig. 242, we find that the wire will rotate in the direction opposite to the hands of the clock. It tends to wind around the pole in such

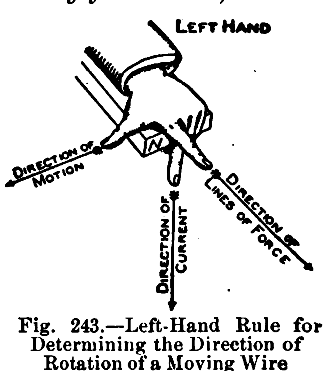

Fig. 243.—Left-Hand Rule for Determining the Direction of Rotation of a Moving Wire in a Magnetic Field.

This rule applies to motors.

a direction as to increase the magnetism of the pole, just as in the automatic twisting experiment, ¶ 266.

This rule is very convenient for determining the direction of rotation of motors, ¶ 358. The moving wire in Fig. 242 is analogous to the armature of the motor, and the electromagnet, its field.

If the direction of current through the armature and field of Fig. 242 be reversed, as by changing the binding post terminals, the direction of rotation will be the same as before, because the current through the moving wire and the polarity of the field are both reversed, therefore, the same relation exists as before, which can be proved by the left-hand rule. If, now, only the current in the wire be reversed, or only the polarity of the field, then the direction of rotation is reversed, as proved by the left-hand rule.

To reverse the direction of rotation of a motor, therefore, *reverse the direction of current either through the armature or the field magnets, but not through both.*

A permanent magnet can be substituted for the electromagnet in Fig. 242, as the same principles are involved. The wooden ring could be lowered to the middle position of the magnet and the wire prolonged when a greater part of its field would be in the magnet's field.

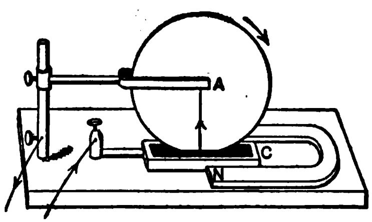

Fig. 244.—Barlow's Wheel.
Faraday's disc dynamo driven as a motor.

If the ring were located on the base, Fig. 242, and the wire, AB, extended the whole length of the magnet, one pole would tend to urge it in one direction and the other pole in the opposite direction, so that if the poles were of equal strength the wire would not rotate.

Another device to produce continuous rotation is illustrated in Fig. 244, and called Barlow's wheel. The edge of a pivoted copper disc dips into a trough of mercury located between the poles of a horseshoe magnet. The magnet's field acts at right angles to the current's field since the current flows from the periphery of the disc to its axis, and the disc rotates in the direction of the hands of a clock, Fig. 244, as can be determined by the left-hand rule.

268. Electrodynamics.—The term *electrodynamics* is applied to the study of that part of electricity which treats of the force exerted by one current upon another. We have just noted the reciprocal action between a current and a magnet, and now in electrodynamics, the mutual action of the currents upon each other is to be considered. Every wire through which a current is flowing is surrounded by a magnetic field, and the magnetic fields of two wires react upon each other. This reaction may take place between two neighboring wires in the same circuit through which a current is

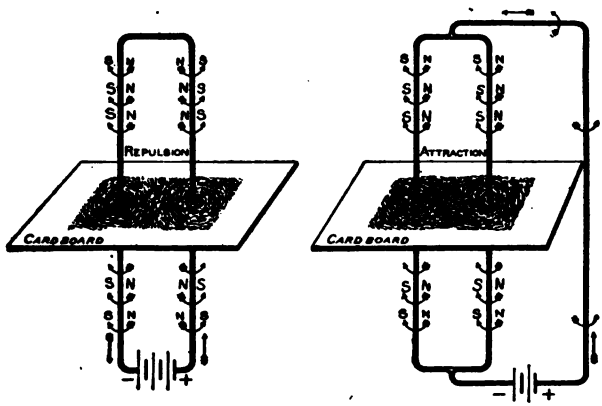

Fig. 245.—Parallel Currents Flowing in the Same Direction Attract Each Other; if in Opposite Directions they Repel Each Other.

flowing, or it may occur between wires in two independent circuits, the action depending on the relation between the two magnetic fields.

269. The Magnetic Fields of Parallel Currents.—The magnetic field of a straight wire carrying a current was illustrated in Fig. 128. If you regard magnetic lines as being of **N**-polarity when their direction is toward you, and of **S**-polarity when their direction is away from you, then when the direction of the whirls is kept in mind, the **N** and **S**-polarity of a straight wire may be readily remembered. In the left-hand diagram of Fig. 245 the direction of the current, the direction of whirls and polarity of the wire are indicated. The wires pass through a piece of cardboard upon which, by the aid of iron filings, the graphical field is made. The cur-

rent in the parallel wires flows in the *opposite* direction, so that the two adjacent sides are of the same polarity, thus causing a force of repulsion to exist between them. The wires tend to move away from each other. The field is very condensed between the wires and elongated outside of them. Midway between the wires the lines of force are in the same direction and fairly uniform for a small area; it is here that the needle of the tangent galvanometer is placed. (Compare with Fig. 139.) The repulsion between the wires may be demonstrated by the following experiment.

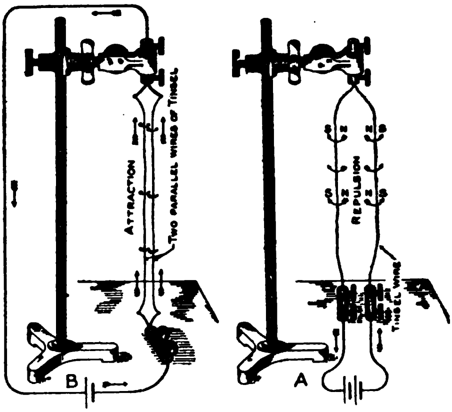

Fig. 246.—Attraction and Repulsion Between Suspended Tinsel Wires Carrying Currents.
A—Currents in the opposite direction—repulsion.
B—Currents in the same direction—attraction.

Exp. 70: Support from a suitable stand a wire connector and suspend from the same two long, parallel, vertical pieces of tinsel wire arranged close to each other and connected to a source of current, A, Fig. 246. When the circuit is closed, the currents being in opposite directions repel each other, and the wires move apart as depicted, according to the principles of ¶ 269.

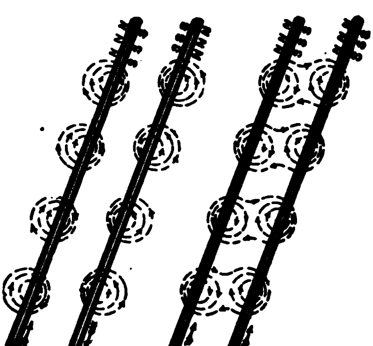
Fig 247.—Attraction and Repulsion Between Parallel Currents.

In the right-hand diagram, Fig. 245, the currents in the parallel wires are in the same direction and the polarities of the adjacent wires unlike, so that attraction results according to the law for unlike polarities. This is noted in the filing diagram, where the field on the outside of the wires is very much condensed and elongated between these

wires. There are also continuous curves embracing both wires, due to the unison of some of the magnetic lines of both wires. The wires tend to be drawn together by the tension along these lines of force. This attraction is demonstrated in Exp. 71.

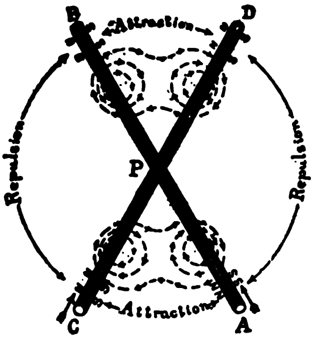

Fig. 248.—Attraction and Repulsion Between Angular Currents.

Exp. 71: Pass the current through the two parallel tinsel wires in B, Fig. 246, in the same direction, and although the wires are separated for some distance they move toward each other, according to the principle in ¶ 269.

270. Laws of Parallel and Angular Currents.

—1. PARALLEL WIRES CARRYING CURRENTS AND FLOWING IN THE SAME DIRECTION ATTRACT EACH OTHER; BUT IF THE CURRENTS ARE IN THE OPPOSITE DIRECTION THEY REPEL EACH OTHER. See Fig. 247. This law is true for independent circuits or for two parts of the same circuit.

2. TWO WIRES CROSSING EACH OTHER AT AN ANGLE ATTRACT EACH OTHER IF THE CURRENTS IN EACH OF THEM FLOW EITHER TOWARD THE POINT OF CROSSING OR AWAY FROM IT; BUT THEY REPEL EACH OTHER WHEN THE CURRENT FLOWS TOWARD IT IN ONE WIRE AND AWAY FROM IT IN THE OTHER. See Fig. 248 and Exp. 74. The motion tends to make the wires not only parallel, but also coincident. This law is very important, and upon its principle are constructed electro-dynamometers and watt meters, ¶¶ 272, 273, etc.

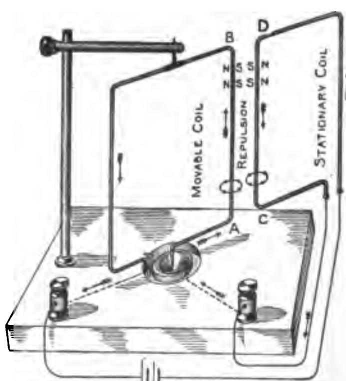

Fig. 249.—The Movable Coil (AB) May be Attracted or Repelled by the Stationary Coil (CD).

3. THE FORCE BETWEEN TWO PARALLEL CURRENTS IS PROPORTIONAL TO THE PRODUCT OF THE CURRENT STRENGTHS AND TO THE LENGTH OF THE WIRES CONSIDERED, AND VARIES INVERSELY

AS THE DISTANCE BETWEEN THEM The first and second laws may be further demonstrated by the ampere-frame coil described in ¶ 175.

Exp. 72: Connect the ampere-frame coil and rectangular coil in series, and to a source of current, Fig. 249. Trace the direction of current in each coil. Hold one side of the rectangular coil, CD, parallel and close to one side of the movable coil, AB. The wire AB is repelled and moves away from CD when the currents are in opposite directions, Fig. 249. Invert the coil CD so that the current flows in the same direction through both, and the movable coil is attracted and will follow CD if it is carried around the axis of the coil AB.

Exp. 73: Roget's Jumping Spiral.—A further proof of the first law is demonstrated by the following apparatus: a phosphor bronze spring is supported vertically by a stand, Fig. 250. The lower end dips into a cup of mercury, MC. Current is passed through the spring and flows around each convolution in the same direction, hence the magnetic fields of all the convolutions attract each other, and the length of the spiral is shortened to such an extent that the lower end is pulled out of the mercury cup, thus breaking the circuit. Gravity now pulls the spring down again and the circuit is re-established, only to be broken by the same action. The spring thus vibrates continuously like the vibrator of an electric bell. An iron rod lowered down through the centre of the spiral, so that it does not touch the convolutions, greatly increases the action by increasing the magnetic effects of the whirls around each wire. In any solenoid or electromagnet, the magnetic field, therefore, tends to bind the wires closer together, as in Roget's spiral, since the current is in the same direction through all the turns, and all the convolutions are parallel.

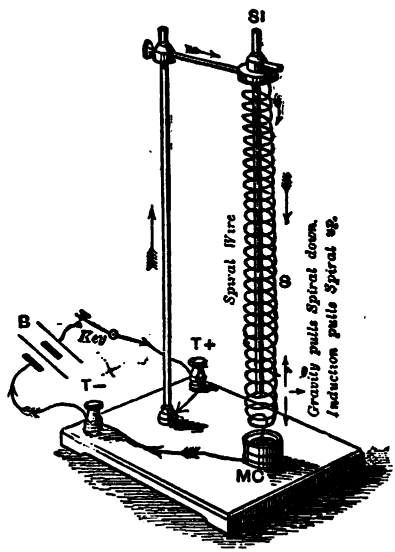

Fig. 250.—Roget's Jumping Spiral.
It illustrates the law of parallel currents flowing in the same direction.

271. Currents in Angular Conductors.—In Fig. 248 two insulated wires AB and CD make an angle with each other, and the currents flow from A and C toward P, and the por-

tions AP and CP attract each other, according to Law 2. This is indicated by the polarity of the wires and the direction of the whirls around them.

Currents also flow away from P, toward B and D, and similar attraction takes place according to Law 2. Now consider the current and polarity in the part of the wire AP and PD. In AP the current flows toward P, and in PD away from P, and repulsion exists as indicated. This law can be experimentally demonstrated by the apparatus described in Exp. 74.

Exp. 74: Inside of the movable rectangular coil AB, Fig. 251, is clamped a fixed coil CD. The two coils may be connected in series or to two independent circuits. The movable coil, AB, is turned so that its plane makes an angle with the plane of the coil, CD. If the current be sent through the coils so that it flows along AB and CD either toward or away from their angle of intersection, the coil, AB, will move in the direction of the arrows till its plane coincides with that of CD, or till they are parallel, according to Law 2. If, now, the current through *either* but not both of them be reversed, the coil, AB, will move against the direction of the arrows and complete one-half revolution, till its plane coincides with CD, when B will be directly above C. This motion is in accordance with the latter half of Law 2, when the currents flow in one wire toward the point of crossing, and in the other wire away from it.

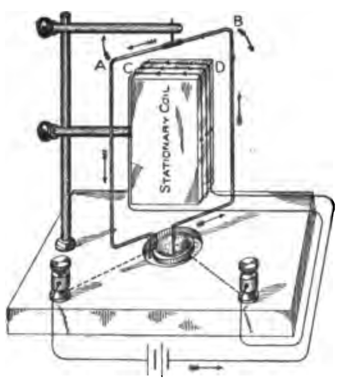

Fig. 251.—Angular Currents Tend to Become Parallel and Flow in the Same Direction.

272. The Electro-Dynamometer.—The electro-dynamometer is an instrument for measuring current strength by the reaction between two coils, one of which is fixed and the other movable, and through which the current to be measured is passed. The general appearance of the laboratory type, known as a *Siemens dynamometer*, is illustrated in Fig. 252, and the diagram of the circuits is shown in Fig. 253. The fixed coil, CD, containing a number of turns of wire is fastened to a vertical support. The movable coil, AB, of a very few turns of wire, is large enough to embrace the fixed coil when their planes are at right angles to each other, and is suspended by a strong piece of thread below the cardboard dial. The ends

of this coil, being free to move, dip into two cups of mercury, located one above the other along the axis of the coil. Connections are made as indicated, so that the two coils are in series when connected to an external circuit. The planes of the coils should be at right angles to each other. When the current flows through both coils, the movable coil tends to turn, according to Law 2 for angular currents.

The force measured is the force which must be applied to keep the movable coil at right angles against the turning effort

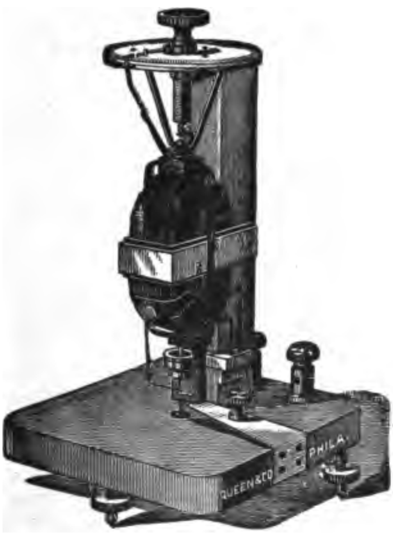

Fig. 252.—Siemens Dynamometer. Laboratory pattern.

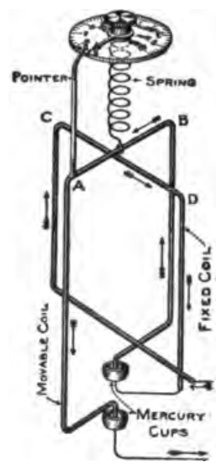

Fig. 253.—Connections of Siemens Dynamometer.

due to the current. One end of a spring, S, is rigidly fastened to the movable coil, and the other end terminates in a mill-headed screw on the face of the dial, which can be turned so as to apply torsion to the spring. The movable coil carries an index pointer bent at right angles, which swings between two stop pins on the dial and rests directly over a fixed zero line when the coils are at right angles. To the torsion screw is attached a pointer which sweeps over a degree scale. When the movable coil is deflected against a stop pin the torsion screw is rotated in a direction to oppose the current's action,

and when the coil is brought back to its original position the number of degrees through which the torsion pointer was turned, is noted.

The current is directly proportional to the square root of the angle of torsion. For example, if with one current the number of degrees noted was 36 and with another current, 144, then the currents are to each other as the square roots of 36 and 144, or as 6 is to 12, or one current is twice as strong as the other. To determine the current in amperes, the square root of the angle of torsion is multiplied by a constant found by calculation and furnished by the makers. The Siemens dynamometer is an accurate instrument connected in circuit like an ammeter and has the advantage of being adapted for use with either direct or alternating currents.

Fig. 254.—Dynamometer Ammeter for Alternating or Direct Currents. Portable Form.

273. Portable Dynamometer Ammeter.—A portable commercial form of electrodynamometer for use as an alternating or direct current ammeter is illustrated in Fig. 254. The operation and principles involved are substantially the same as those given for the Siemens dynamometer, ¶ 272, but the scale is graduated to read directly in amperes. When used on a direct current circuit more accurate results are obtained by taking the average value of two readings made with the current reversed. The fixed coil is divided into two coils wound with a different number of turns, each of which is inserted in series with the movable coil and brought out to separate posts. Thus, if it is desired to measure a current known to be between one-tenth and 1 ampere, the right-hand binding posts are used, and if between 1 and 100 amperes, the left-hand posts are used. This arrangement produces a double scale instrument whereby a small current can be measured with much greater accuracy.

274. Dynamometer Wattmeter.—The energy in watts

expended in a circuit is equal to the product of the volts, E, and the current I, or W = E × I, Formula (62). These factors may be determined by a volt and an ammeter and multiplied together, or the multiplication may be automatically performed by using a form of Siemens dynamometer which measures the watts directly, and is, therefore called an indicating wattmeter. Siemens dynamometer wattmeter operates upon the same principles as the dynamometer ammeter, ¶ 272, but the two coils are not connected in series. The *stationary coil*, or the ampere coil, is connected in series with the line like an ammeter, Fig. 255, and is wound with a few turns of *heavy wire* having a *low resistance*. These terminals are brought out to two binding posts, as shown at the left of the Weston direct reading portable wattmeter, Fig. 256. The *movable coil*, or volt coil, is wound with a few turns of very *fine wire* and connected in series with a *high resistance*, the terminals being brought out to independent binding posts, as shown at the top of the Weston instrument. A push button switch is inserted in the volt coil circuit. The movable coil thus corresponds to the voltmeter and is connected to any circuit in the same manner as a voltmeter.

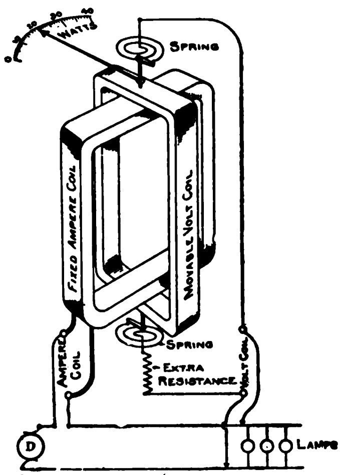

Fig. 255.—Connections of a Dynamometer Indicating Wattmeter.


Fig. 256.—Weston Direct Reading Wattmeter.

The current in the volt coil will vary as the potential difference between its terminals and the current through the ampere coil will vary as the current in the circuit in which it is inserted. The force acting upon the movable coil, or the force required to bring it to zero, depends on the current through both coils, or directly upon the watts expended in them. In the Weston portable instrument the movable coil is constructed and mounted similar to the coil shown in Fig. 198. The movable coil turns against the torsion of the spring and its pointer swings over a scale graduated in watts. The instrument is, therefore, direct reading, as in the case of a voltmeter. In Fig. 255 the proper connections of the instrument for measuring the watts consumed by the incandescent lamps are shown. The pointer indicates the watt consumption by the lamps. (Compare with Fig. 214.)

The Weston instrument requires no adjustment to secure a balance of the forces acting, and so momentary fluctuations are readily noted on the scale. This instrument can be used on any circuit and is rated according to the carrying capacity of the ampere coil and the potential to be applied across the volt coil. For example, in a 1500-watt instrument the maximum current is 10 amperes and the maximum voltage 150 volts. The capacity of the volt coil can be increased to any desired range by the use of a portable box of extra resistances, called a *multiplier*, connected in series with it.

275. Thomson Recording Wattmeter.—The Weston indicating wattmeter, ¶ 274, gives the instantaneous values of the watts expended in a circuit, just as a voltmeter indicates the fluctuations in volts. To find the watt-hours consumption of electrical energy by such a meter, it will be necessary to multiply the average of a number of readings taken during a given time, by that time, expressed in hours, ¶ 223. As the name implies, the readings of a Thomson recording wattmeter, give the total watt-hours consumption of energy, or it automatically multiplies the average of the instantaneous indications by the time. It is, more correctly speaking, therefore, a joulemeter, ¶ 217. Its principle of operation is that of the Siemens dynamometer, ¶ 272, but, the movable coil rotates. The method of producing this rotation may be demonstrated as follows:

In Fig. 251 continuous rotation of the coil, AB, around the coil, CD, could be produced, if at each instant the coil, AB, became par-

allel to CD, the current were automatically reversed through it. With the single turn and a strong current, sufficient repulsive impulse would be produced to move it through 180°: if the current be now reversed it will receive a similar repulsive impulse and will be repelled through another 180°, and so on. There will thus be two reversals and two impulses given to the movable coil each revolution, and continuous rotation produced. The force producing the rotation will still be dependent upon the current in both coils as in the dynamometer. A uniform force for producing rotation would require several coils similar to AB and arranged about a vertical axis, with their planes at angles to each other, so that as one coil moved away from the stationary coil another would take its place. Such an arrangement would be practically a motor, the moving coils forming the *armature* and the stationary coil the *field*. A worm on the armature shaft engaging with the train of wheels of a cyclometer dial would record the speed, and since the number of revolutions in an hour depends on the current through the coils during that time the cyclometer dial could be calibrated in watt-hours, provided the speed were proportional to the energy supplied.

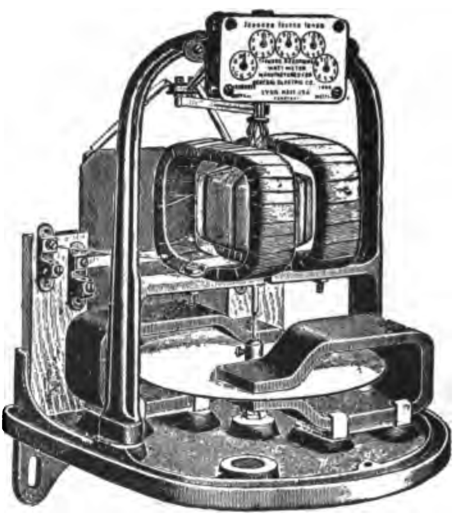

Fig. 257.—Thomson Recording Wattmeter with Case Removed.

The Thomson recording wattmeter is a simple type of motor, driven by the same electrical energy which it is to measure; its rotation during any period is proportional to the power in watts delivered to the circuit during that time. The movable coil or armature revolves between two stationary coils with its axis at right angles to the axes of these coils, as shown in Fig. 257, where the meter cover is removed. The movable coil, Fig. 258, is a drum-wound armature, ¶ 328, without an iron core, and the current through its coils is reversed automatically by the commutator, ¶ 323, thus causing it to revolve. Current is led to the commutator by the wiping

contacts or *brushes*, B. A worm, S, on the upper end of the armature shaft engages a set of wheels which records the watt-hours on a dial. The armature is very light and delicately poised between jewel centres, so that the friction is reduced to a minimum here as well as in the train of wheels.

To the lower end of its shaft is rigidly fixed, at right angles, a copper disc which rotates with it in the magnetic field of three permanent stationary steel horseshoe magnets. The **N**-poles of these magnets are above and the **S**-poles below the copper disc, and it cuts the magnetic lines of force as it revolves. Eddy currents, ¶ 292, are induced in the copper disc, and the reaction of their magnetic field tends to retard the rotation. The amount of this retarding effect is directly proportional to the speed of rotation. Since the angular force causing the armature to rotate is directly proportional to the magnetic field of the currents in the two coils, and the retarding angular force also proportional to the magnetic field set up, the armature must rotate at such a speed that the electromagnetic driving torque is exactly equal to the electromagnetic retarding torque. Then with a constant pressure maintained in the wattmeter coils for any length of time, the number of revolutions of the armature, and therefore the travel of the dial hands will also be constant during the time, and proportional to the energy supplied.

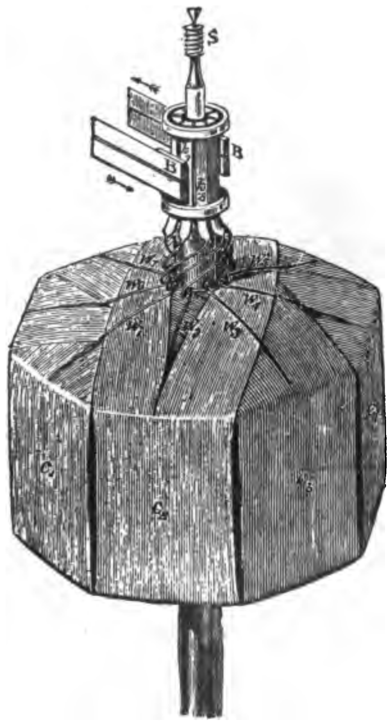

Fig. 258.—Drum-Wound Armature of Thomson Recording Wattmeter.

A high resistance is inserted in series with the armature and it is connected to a circuit just like the volt coil of the indicating wattmeter in Fig. 255. The stationary current coils are wound in the same direction to produce the field, and are connected in series with the circuit, as in Fig. 259. The meter dials are graduated in watt-hours and read like a gas meter. The speed of the motor is materially reduced by the drag produced by the copper disc so that the dial reading is multiplied by a constant, the value of which is given on the dial; a constant of 6, therefore, means that the meter dial has recorded only 1-6 of the energy and its indication must be multiplied by 6 to obtain the true watt-hour consumption. The constant is used to avoid a high speed of rotation. Thomson wattmeters can be used on alternating or direct current circuits, and are made in different sizes according to the current carrying capacity of the ampere coil. The amount of extra resistance in the armature circuit depends on the voltage to which it is to be subjected. These meters are extensively used on commercial motor circuits and in individual house electric light service, similar to a gas meter, and are sensitive enough to record the energy through even one lamp when connected to the supply circuit.

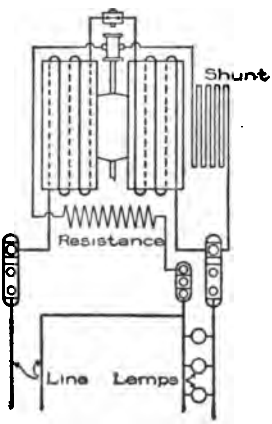

Fig. 259.—Connections of a Thomson Recording Wattmeter.

QUESTIONS.

1. Two parallel wires are stretched from vertical supports, the measured distance between them being 2 inches. A current is sent through the wires, and the distance is now only $1\frac{3}{4}$ inches. How do you explain this?
2. What is the direction of the current in the wires in question 1?
3. The current is reversed in both wires in question 1. How will they now be affected?
4. Make a complete sketch of a Thomson recording wattmeter connected between the two street mains, entering a consumer's building, and the parallel lamp circuit.
5. A Siemens dynamometer is connected in series with some incandescent lamps and the torsion head must be turned through 121°

to bring the movable coil to zero position. Some lamps are now turned off and the angle corresponding with the zero position is 81°. The constant of the instrument is 2. What is the strength of current in each case? *Ans.* 22; 18 amperes.

6. Make sketch in detail of a Weston indicating wattmeter connected to a motor circuit so as to indicate the power being absorbed.

7. Two wires cross each other at an angle of 60° and the current flows through them in an opposite direction. Will they tend to move so as to increase or decrease the angle of crossing?

8. What is the advantage of a dynamometer ammeter over one constructed upon the D'Arsonval principle?

9. Explain the difference between an indicating and recording wattmeter, stating the principles involved in each.

10. A vertical wire carrying a current rotates around the S-pole of a magnet in a direction against the hands of a clock as viewed from the S-pole end. Is the current flowing up or down the wire?

11. A copper disc is mounted between the poles of a horseshoe magnet and current passed from its centre to the circumference. Make a sketch indicating the direction in which the disc will rotate.

12. How can you change the direction of rotation of the disc in question 11?

13. Make complete sketch of connections of a double scale dynamometer ammeter.

14. Current is passed downward through a vertical wire, and a bar magnet with its N-pole held uppermost is placed near to and parallel with the wire. Suppose the magnet to be flexible, like a piece of tinsel, what will occur? Make sketch.

LESSON XXIV.

ELECTROMAGNETIC INDUCTION.

Electromagnetic Induction—Currents Induced by a Magnet in a Wire—To Find the Direction of the Induced Current (Fleming's Right-hand Rule)—Upon What Factors the Value of the Induced E. M. F. Depends—Currents Induced in a Coil by Motion of a Magnet—Primary and Secondary Coils—Lenz's Law of Induced Currents—Classification of Induction Currents—Currents Induced by Electromagnetism—Five Methods of Producing Induced Currents—Table of Induction Currents—Variation of Induced E. M. F., with the Rate of Change of Magnetic Lines of Force (Faraday's Law)—Eddy Currents (Arago's Rotations)—Mutual Induction—Self-Induction—Gas Lighting Spark Coil—Inductance—Reactance and Impedance—Choke Coils—Neutralizing the Effects of Self-Induction—Questions and Problems.

276. Electromagnetic Induction.—In Lesson XV a current of electricity flowing through a wire was found to set up around the wire a magnetic field, Fig. 129. The magnetic field was maintained around the wire at the expense of chemicals inside the cell. If a wire be arranged so as to form a closed circuit and then moved across a magnetic field, a current of electricity is produced in the wire; in other words, if we artificially produce around the wire the magnetic whirls, a current of electricity flows through it when the circuit is complete. The English physicist, Michael Faraday, discovered (in 1831) that electric currents could be induced in a closed circuit by moving magnets near it, or by moving the circuit across a magnetic field. Currents that are so generated are known as *induction currents* and the phenomenon termed *electromagnetic induction.* (Compare with magnetic induction, ¶ 36.) This is a most interesting and valuable branch of the study of electricity, as upon its principles is based the operation of many forms of commercial electrical apparatus, such as dynamos, transformers or induction coils, telephones, etc.

277. Currents Induced in a Wire by a Magnet.—A sensitive galvanometer, G, Fig. 260, is removed from the in-

fluence of the bar magnet, NS, and connected by a piece of copper wire. If a portion of the wire, AB, is *quickly moved down* past the pole of the magnet a *momentary current* is induced in the wire, causing the galvanometer needle to be deflected, say to the right of zero, when it will again return to the zero position. If the wire is again *moved up* past the same pole another *momentary current* is induced in the wire in the *opposite direction* to the former current, as indicated by the *momentary deflection* of the galvanometer needle, which now swings to the left of zero. If the induced current, then, flows from A to B on the downward motion it will flow from B to A on the upward motion. If the wire be moved rapidly up and down past the magnet, the current will alternate in direction with each direction of motion, or an *alternating current*, ¶ 320, will be induced in the wire. When this motion is rapid, and consequently the alternations, the needle does not have sufficient time to take up the respective positions due to the opposite currents flowing around it, and, therefore, remains at zero, appreciably vibrating, however. The induced current is constant, but alternating in direction.

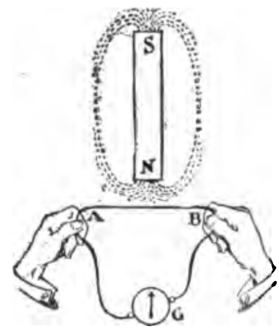

Fig. 260.—Current Induced in a Wire by Moving it Past a Magnet.

(1.) *If the wire is held stationary and the magnet moved, the same results are noted.*

(2.) *If the opposite pole is used, the direction of the current in each instance is opposite to what it was before.*

(3.) *An electromagnet used instead of the permanent bar magnet will produce the same results.*

(4.) *The induced current does not weaken the magnet, but is produced by the expenditure of muscular energy, just as in a cell the current is produced by the expenditure of chemical energy.*

(5.) *The momentary induced current is greatest when the wire is moved so as to cut the magnetic lines of force at right angles.*

(6.) *The direction of current in the wire is at right angles to the direction of the lines of force of the magnet.*

(7.) *Current in any wire depends upon the E. M. F. causing it to flow, so that properly speaking, an E. M. F. is induced in the*

wire when it is made to cut magnetic lines of force, and a current flows when the circuit is complete, due to this induced E. M. F.

(8.) *If the wire is cut at any point, in Fig. 260, an E. M. F. is maintained at the terminals of the wire, when motion occurs, just as an E. M. F. exists at the terminals of a cell on open circuit tending to cause a current to flow,* ¶ 70.

278. To Find the Direction of the Induced Current.—FLEMING'S RIGHT-HAND RULE.—*Place the thumb, the first and second fingers of the right hand all at right angles to each other, Fig.* 261, *and in such relation to the wire that the first finger points in the direction of the lines of* FORCE *of the magnet, and the thumb, in the direction of motion; the* SECOND FINGER *will then indicate the* DIRECTION OF THE INDUCED CURRENT.

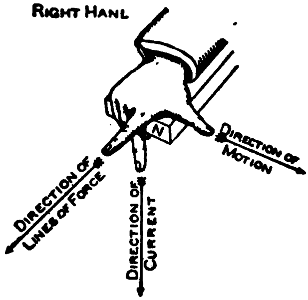

Fig. 261.—Right-Hand Rule for Determining the Direction of Induced Current—Fleming's Rule.

Applying this rule to the wire, AB, Fig. 262, which is being moved down past the **N**-pole of the magnet we find that the direction of current is *from* B *toward* A. If either the polarity *or* direction of motion be reversed, the current in the wire AB will be reversed, as can be proved by this rule. If both the polarity and motion are reversed the current is in the same direction as in the figure. The student should prove these statements by the above rule.

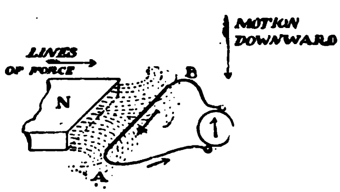

Fig. 262.—Application of Fleming's Rule.

Another method of ascertaining the direction of the induced current is to keep in mind the direction of the magnetic whirls around the wire, corresponding to the direction of current through it as you look along the wire, Fig. 136. If you look along the wire *from* A *toward* B, Fig. 262, while it is being moved *downward* across the lines of force, the direction of these lines underneath the wire is from *left* to *right*, and the direction of motion such that if the magnetic lines were flexible they would be wrapped around the conductor in a direction *opposed to the* motion of the hands of a clock. Since the tendency of the induction is, in this case, to produce magnetic whirls, the direction of which is *anti-clockwise* as you look along the wire, the current set up flows toward you, or from B toward A. (Compare with Fig. 130.)

279. Value of the Induced E. M. F.—The magnitude of the induced E. M. F. generated in a conductor when it is cutting lines of force is *proportional* to the rate at which the lines of force are cut. *When a conductor cuts lines of force at the rate of 100,000,000 per second, a pressure of one volt is set up between the terminals.*

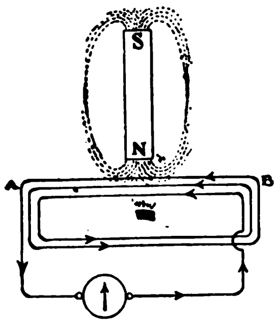

Fig. 263.—Increasing the Induced E. M. F. by Increasing the Number of Cutting Wires.

If a single conductor is moved across a magnetic field, the number of lines of force cut per second by the conductor would equal the total number of lines of force contained in the field, divided by the time in seconds required to move the conductor across the field. The number of lines of force cut by a wire in one second moving in a magnetic field depends upon the strength of the field; that is, the number of lines of force it contains and the speed at which the wire is moved. The number of lines cut will also depend upon the length of the wire, and upon the angle which the wire moves across the field, ¶ 291. If a wire cuts a certain number of lines of force per second, causing a pressure of one volt to be set up between its ends, and there are five similar wires joined in series and moved so as to cut the same number of lines per second as the single wire, five times the pressure would be set up, or, five volts.

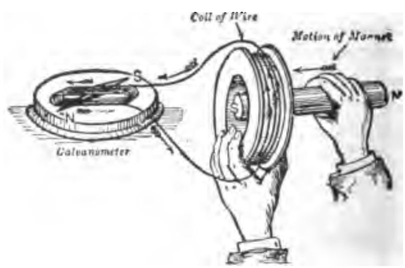

Fig. 264.—The Polarity of the Induced Current Tends to Stop the Motion Producing It—Lenz's Law.

The induced E. M. F. will, therefore, depend upon the following factors:

(*a*) *The strength of the field (the number of lines of force it contains)*;

(*b*) *The speed or rate of cutting (number of lines of force cut per second)*;

(*c*) *The number of wires cutting the lines of force.*

280. Currents Induced in a Coil by Motion of a Magnet.—Instead of moving the wire down past the magnet in Fig. 260, the wire may be coiled up, as in the solenoid, Figs. 264 and 266, and connected to the galvanometer. If a permanent or an electromagnet be thrust into the

solenoid, a momentary induced current flows around the galvanometer according to the conditions given in ¶ 277.

Exp. 75: Connect the student's galvanometer, Fig. 153, to the secondary coil, Fig. 266, and using the bar magnet set, Fig. 13, make experiments to verify all the statements given in ¶ 277.

Exp. 76: With the same apparatus as in Exp. 75, prove statements (a) and (b) in ¶ 279. Using one magnet, the momentary deflections of the needle will be about 25 for an average thrust.

Exp. 77: To prove statement (c), ¶ 279, substitute for the secondary coil used in Exp. 75 the solenoid depicted in Fig. 145, which contains a different number of turns of wire.

Exp. 78: Connect a cell to the detector galvanometer, Fig. 153, and note whether the needle is deflected to the right or left of zero when the current enters by the right-hand binding post. Having determined the direction of deflection for a particular direction of current through the instrument, substitute for the cell the secondary coil, and repeat the experiments enumerated in ¶ 277. Find the direction of the induced current in the coil by tracing the direction of the winding, noting the direction of deflection of the galvanometer needle and using Fleming's right-hand rule, ¶ 278. Make note-book sketches.

281. Primary and Secondary Coils.—The word *primary* is often used as an abbreviation for *primary coil.* The *primary coil* is the coil producing the induction, or it is the inducing body, while the *secondary coil,* or *secondary,* is the body under induction. In Fig. 264 the bar magnet is the primary body and the coil, the secondary body. In Fig. 266 an electromagnet is substituted for the bar magnet, and is called the *primary coil.*

282. Lenz's Law of Induced Currents.—If Exp. 78 be carefully performed it will be found that, as the **N**-pole of a magnet is thrust toward the coil, the direction of the induced current will be such as to make the face of the coil near to the magnet's pole of the *same polarity* as that pole, Fig. 264; hence, *there is a magnetic repulsion between the magnet and the coil when one is being approached to the other.* When the magnet's pole is withdrawn the *direction* of the *induced current is reversed;* the face near the magnet has now, therefore, *opposite polarity* to the pole of the magnet, and consequently *attraction exists* between them. *In each instance the magnetic attractions or repulsions tend to oppose the motion of the magnet.* The above statements are expressed concisely in LENZ'S LAW, as follows:

IN ALL CASES OF ELECTROMAGNETIC INDUCTION THE DIRECTION OF THE INDUCED CURRENT IS SUCH AS TO TEND TO STOP THE MOTION PRODUCING IT. To produce the induced current

energy must be expended in bringing the magnet to the coil and in taking it away. If the magnet is made to approach by hand, muscular energy is expended; if attached to the end of the piston rod of a steam engine and moved in and out of the coil, mechanical energy is expended and a constant but alternating current produced. It will also be seen that if the coil terminals are open or disconnected very little energy will be required to move the magnet, since there will now be no attractions and repulsions to overcome.

The extra energy required when the coil is closed is expended in producing the induced current, and it is in this way that *mechanical energy is converted into electrical energy in the dynamo.* It will be further noted that with a given rate of motion the alternating E. M. F. will be constant, and, since the resistance of the coil is constant, the current will also be constant. Suppose a galvanometer of much lower resistance is connected to the coil, Fig. 264. The current will now be greater, since the resistance is decreased, and, consequently, the watts will be greater, $W = E \times C$, so that more energy must be expended in producing the E. M. F. than before, because the magnetic field of the coil to be overcome has been increased by the increase of current strength. *When lamps are added in parallel to the circuit of a dynamo the resistance of the circuit is lowered, Formula* (43), *therefore the E. M. F. causes more current to flow through the lower resistance and more mechanical energy must be expended in proportion to the additional electrical energy furnished.*

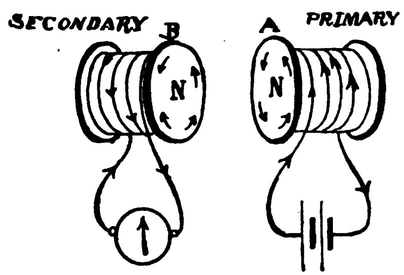

Fig 265.—The Polarity of the Induced Current Tends to Stop the Motion Producing It.—Lenz's Law.

Lenz's Law is further illustrated in Fig. 265, where the primary body, A, is an electromagnet with its polarity as indicated. On moving this electromagnet *toward* the secondary coil, B, the induced current flows so as to make the near face of B of **N**-polarity, and *repulsion* results as before. During the *recession* of the primary from the secondary coil the polarity of the secondary is *reversed* and *attraction* exists, *opposing*

their separation. The attractions and repulsions take place only while the coil is moving. If the coil stops the induced current in the secondary also stops, even though the current still flows in the primary coil. See also ¶ 292.

283. Classification of Induction Currents.—Induction is produced whenever a conductor is cut by magnetic lines of force, no matter how this cutting may be accomplished. The induction resulting from different combinations of moving magnetic fields and conductors may be classified as follows:

(a) *Magneto-electric induction,*
(b) *Electromagnetic induction,*
(c) *Mutual induction,*
(d) *Self-induction.*

In *magneto-electric induction* a permanent magnet is used to produce the magnetic field, and either the wire or the field may be moved to produce induction.

In *electromagnetic induction* the magnetic field of a current or an electromagnet is utilized to produce the induction. Mutual induction and self-induction are defined in ¶¶ 293 and 294 respectively.

284. Currents Induced by Electromagnetism.—Momentary induction may be produced in the secondary circuit of the student's induction coil, Fig. 266, by any of the following methods:

1. *By moving either the primary or secondary circuit.*

When both coils are stationary and one surrounds the other:

2. *By making or breaking the primary circuit.*

3. *By altering the strength of the current in the primary circuit.*

4. *By rapidly reversing the direction of the current in the primary circuit.*

5. *By moving the iron core when a current is flowing through the primary circuit.*

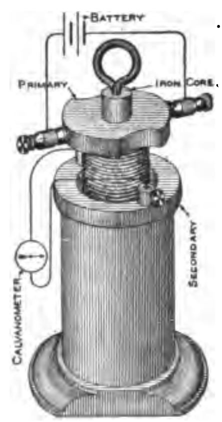

Fig. 266.—Student's Experimental Induction Coil.

A *momentary induced current* which flows in the opposite direction to that of the current producing it, is defined as an *inverse current*, and one which flows in the same direction, a *direct current.* The above methods for producing induction are treated in the following paragraphs.

A simple form of student's induction coil is illustrated in Fig. 266. The primary is a wooden spool wound with 2 layers of No. 15 B. & S. insulated copper wire, with the terminals securely fastened to binding posts, which are mounted at right angles to the coil. The latter is drilled to permit free movement of a three-eighth inch soft iron core to which is attached a brass eye bolt. Resistance of primary is about .07 ohm. Six layers of No. 30 B. & S. wire are wound on the secondary coil, which has a resistance of about 20 ohms.

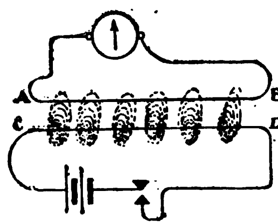

Fig. 267.—The Magnetic Field of the Primary (CD) Cuts the Secondary (AB).

285. First Method.—*Moving Either the Primary or Secondary Circuit.*—When either the primary or secondary circuit is moved relatively to the other the results are the same as those given for a permanent magnet in ¶ 277, and should be verified by the apparatus shown in Fig. 266. The principle involved may be further explained as follows: consider the switch closed in the primary circuit, CD, of Fig. 267; magnetic whirls surround the wire as in Fig. 129. Now move the secondary wire, AB, *toward* CD, and it is cut by the lines of force of the primary circuit, producing a momentary current during the motion. The direction of this induced current is opposed to that of the primary current as indicated, Fig. 268, and it is an *inverse* current. If the secondary be moved *away* from the primary, Fig. 269, the secondary circuit is again cut by the primary, and a *direct* momentary current is induced.

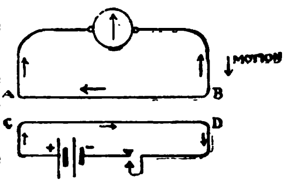

Fig. 268.—Inverse Induced Secondary Current.

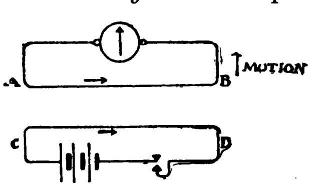

Fig. 269.—Direct Induced Secondary Current.

286. Second Method.—*Making or Breaking the Primary Circuit.*—Consider both circuits stationary in Fig. 267. At the instant the switch is closed the magnetic lines of force springing from the primary, CD, cut the secondary circuit, AB, and an inverse momentary current flows through the secondary, left-hand diagram, Fig. 270, for the period of time required

to establish the electromagnetic field around the primary, ¶ 315. When the switch is opened the magnetic lines of the primary will collapse upon it and again cut the secondary, but in the opposite direction, producing a direct

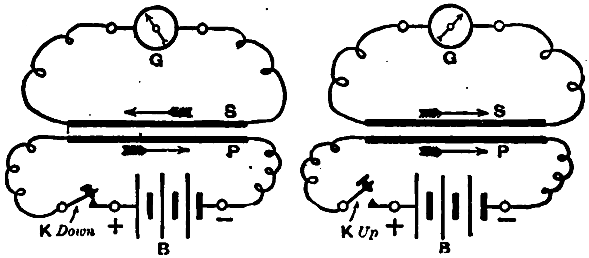

Fig. 270.—Inverse Induced Current on "Make" of Circuit, Direct Current on "Break."

current, right-hand diagram, Fig. 270. If the primary switch be automatically closed and opened a great many times per second, the momentary induced currents will become constant in duration, but will change their direction with

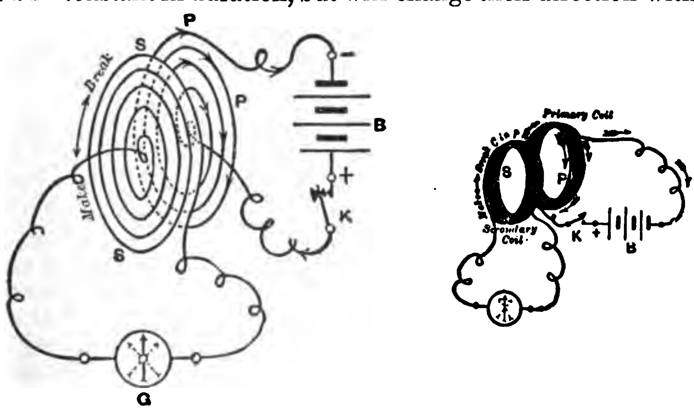

Fig. 271.—Direction of Momentary Induced Currents in the Secondary Circuit.

each make and break of the primary. Whether the circuits are wound in flat spirals or in cylindrical coils, Fig. 271, the same principles apply. The induction coil, ¶ 300, is constructed on this principle.

287. Third Method.—*Altering the Strength of the Pri-*

mary Current.—If a rheostat be introduced into the primary circuit the current can be altered without breaking the circuit, Fig. 272. When the resistance is *decreased* a momentary *inverse* current is induced in the secondary circuit, since the *magnetic lines* of the primary at the instant of change in resistance *are greater* than before, or spring outward. With an increase in resistance the primary lines cut the secondary in the *opposite direction* as they collapse toward the primary wire, and a direct momentary current is induced.

288. Fourth Method.—*Reversing the Direction of the Primary Current.*—A switch arranged to automatically reverse the primary current many times per second would produce an *alternating current*, the magnetic whirls of which would be continually rising, falling, and changing their direction with each reversal. A secondary wire brought into the vicinity of a wire carrying such a current would be continually cut by its magnetic lines of force, and a constant induced alternating current obtained, the variations of which would be like those in the primary circuit. When an electromagnet is supplied with an alternating current, the polarity reverses with each reversal of current so that the magnet's field is continually in motion, and will cut any conductor in its vicinity. The alternating current transformer is dependent on this principle and an alternating current dynamo, ¶ 320, generates a current of this character.

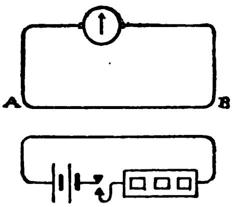

Fig. 272.—Momentary Induced Currents by Varying Strength of Primary Current.

289. Fifth Method.—*Moving the Iron Core.*—If a piece of iron be so moved, relatively to the primary and secondary circuits, that it increases the magnetic lines of force of the primary wire, an inverse current is induced in the secondary, lasting only while the increase takes place. When moved so as to produce a decrease of primary lines a direct induced current results. This principle is used in an *inductor type of an alternating current generator.* The induction is produced by rotating iron poles between the stationary primary and secondary circuits.

290.—Table of Induction Currents.—The character and methods of producing induced currents are summarized as follows :

Table XVIII.—Induction Currents.

By means of	Momentary INVERSE currents are induced in secondary circuit.	Momentary DIRECT currents are induced in secondary circuit.
Magnet.	While *approaching.*	While *receding.*
Current.	While approaching or beginning or increasing in strength.	While receding or ending or decreasing in strength.

Exp. 79: With the student's induction coil, Fig. 266, all of the above cases should be verified and the results noted. To ascertain whether the induced current is a direct or inverse one the relation between the galvanometer deflection and the current should be determined, as in Exp. 78.

291. Variation of Induced E. M. F. with the Rate of Change of Magnetic Lines of Force.—*Faraday's Law.*—To produce induction in a closed coil located in a magnetic field it must be so moved that the number of lines of force threading through it are constantly changing.

The induced E. M. F. is proportional to the rate of change of the magnetic lines threading through the coil. For example, take the closed coil of wire, A, Fig. 273, located in a *uniform* magnetic

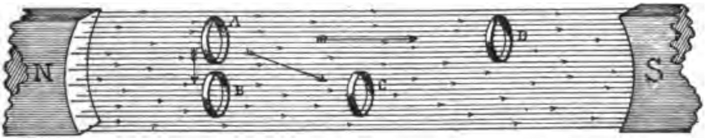

Fig. 273.—No Induced Current in a Loop When Moved so That There is No Rate of Change of the Magnetic Lines Through It.

field, NS, with its plane at right angles to the lines of force. When the coil is moved vertically downward across the field to position B, magnetic lines of force are cut, but no induction results since the number of lines of force threading through the coil have not been altered.

From another standpoint the upper half of the coil cuts the lines in the *same direction* as the lower half, consequently the direction of the induced E. M. F. in each half is the same, or the E. M. F.'s are opposed to each other, and, being of the same value, no current can flow. If the coil A be held either

in a vertical position or at an angle, and then moved across the field in the direction of the arrows to either position, D or C, no induction will take place for the same reasons. If the coil be now turned through any angle to its vertical position, say 45°, as shown in position B, Fig. 274, *the number of lines of force threading through it are altered* (decreased), and during the angular motion an induced current flows around the ring in the direction of the arrow. In this case each half of the coil cuts the lines of force in an opposite direction, consequently the induced E. M. F.'s are also opposite in direction and in series with each other. The current, therefore, flows around the ring.

When moved through the next 45°, or from B to C, the rate of change of magnetic lines through the coil continues, and is greater than when it is moved from A to B. This will be seen by noting the comparative number of lines above coil B, which pass over it instead of threading through it at

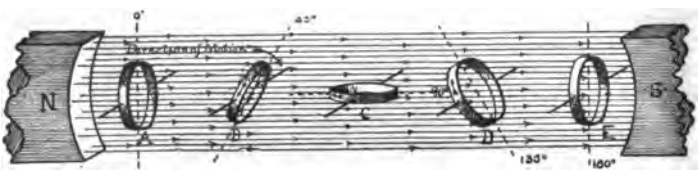

Fig. 274.—Phases of Induction in a Closed Loop When Rotated in a Magnetic Field—Principle of the Dynamo.

this angle of inclination, 45°, and have, therefore, been emptied out. At the position of coil C, all the lines of force above it have been emptied out of the coil. The rate of change at this position is a maximum, and the induced E. M. F. then varies from 0 in position A, to its maximum value at position C, 90° from A. If the motion be continued from C to D, many lines of force will now be emptied into it and induction will occur. The direction of the induced current is indicated, and is found by Fleming's rule. The induced E. M. F. gradually decreases during the motion from C to D, because the rate of change in the number of the lines of force increases in the same ratio as it decreased during motion from B to C. Motion from D to E corresponds to that from A to B, and in E all the lines are again flowing through the loop, causing no induction at this position, since there is no rate of change. During the revolution of the coil through

180°, from position A to E, the E. M. F. gradually increases from 0 to a maximum of 90°, and gradually decreases again to 0 at 180°. The same will be true of the second half of the revolution, 180° to 360°, except that the direction of current is the *reverse*, since moving a conductor up past lines of force produces an opposite direction of current from that obtained when it is moved down past the same lines. In one revolution of the coil there are thus two alternations of current, and two points of maximum E. M. F., at 90° and 270°, and two points of zero E. M. F.—that is, when the current changes its direction at 0° and 180°. When this loop is mounted on a shaft and so rotated, we have the principle of a simple *alternating current* dynamo, or alternator, ¶ 320.

Faraday's Law is as follows: LET ANY CONDUCTING CIRCUIT BE PLACED IN A MAGNETIC FIELD; THEN IF BY A CHANGE IN POSITION OR A CHANGE IN THE STRENGTH OF

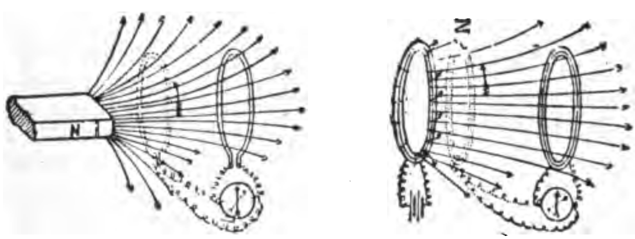

Fig. 275.—The Induced E. M. F. Depends Upon the Rate of Change of the Magnetic Lines Through the Loop—Faraday's Law.

FIELD, THE NUMBER OF LINES OF MAGNETIC FORCE PASSING THROUGH OR INTERLINKED WITH THE CIRCUIT IS ALTERED, AN E. M. F. WILL BE INDUCED IN THE CIRCUIT PROPORTIONAL TO THE RATE AT WHICH THE NUMBER OF LINES IS ALTERED. By referring to Fig. 275, it will be understood how Faraday's Law applies to all our previous induction experiments. In the positions of the secondary circuits shown by the solid lines, the number of lines through them is a minimum. When moved up close to the primary, as in the dotted positions, a great many more lines fill the coils, which are also emptied out again during recession.

Lenz's Law, ¶ 282, may also be applied to the motion of the coil in Fig. 274. The direction of current indicated by the arrows on the rings is found by Fleming's rule, and is

such that if the ring be viewed from the **N**-pole side as it is being moved away from this pole the induced current flows around it clockwise, producing a **S**-pole on this face with resulting attraction for the **N**-pole, from which it is receding. Muscular or mechanical energy must, therefore, be expended in moving the ring through the angular position in proportion to the electrical energy developed in it.

292. Eddy Currents—Arago's Rotations.—When a magnet is suspended over a copper disc and the disc rotated, induced currents are generated in the disc, which tend to oppose the motion producing them. If the magnet be free to move it will be dragged around in the same direction that the disc rotates. According to Lenz's Law, the direction of the current in the part of the disc moving toward the magnet pole will be of the same polarity as the pole being approached, therefore tending to repel the magnet, while that in the receding part of the disc will be of the opposite polarity, thus attracting the magnet. Both actions, then, tend to urge the magnet in the same direction and to cause its rotation. If the magnet be held stationary and the disc revolved, considerably more force must be applied to turn it than when the magnet is not near it. Each part of the disc, as it comes under the influence of the magnet, is subjected to rapidly succeeding increases and decreases in the number of lines of force threading it.

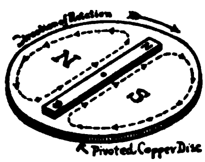

Fig. 276.—Eddy Currents Induced in a Copper Disc Rotated Under a Stationary Permanent Magnet.

Such currents induced in masses of metals either by being rapidly cut by the moving field or by moving in the field are called *eddy currents*. The direction of the eddy currents in the copper disc for a particular case is shown in Fig. 276. The magnet is stationary and the disc rotated clockwise. The currents circulate around the disc in the form of two semi-circles. In the left-hand one the direction is anti-clockwise, producing a **N**-face on the disc which repels the **N**-pole of the magnet, and tends to stop the motion producing it. On the right-hand side a **S**-face is produced, attracting the **N**-pole, and again tending to stop the motion of the disc, according to Lenz's Law. When the magnet is free to move, it will tend to move so that its poles will always be over the unlike poles induced in the disc, but as soon as

the magnet moves the paths of the eddy currents also change. They will always be set up with the magnet as their diameter, and each half of the disc will be of opposite polarity. The position which the magnet seeks is never attained and continuous rotation results as long as the disc is rotated. If pieces of wire gauze are pressed against the disc directly under each pole of the stationary magnet, Fig. 276, forming wiping contacts, or *brushes*, and the brushes connected to a galvanometer, the needle will be deflected by the eddy currents when the disc is rotated.

Faraday's disc dynamo consisted of a copper disc rotated between the two poles of a magnet, Fig. 277, the current being led off from the centre and edge of the disc by brushes. Barlow's wheel, Fig. 244, when rotated by hand will give current to an external circuit, illustrating the convertibility of a motor and dynamo. When electromagnets are used they must be excited by a separate source of current.

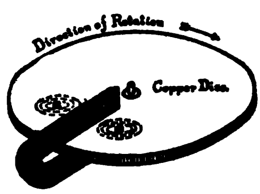

Fig. 277.—The Eddy Currents Tend to Oppose the Motion Producing Them.

A compass needle in a metal case will come to rest very quickly, because by its oscillating motion it induces eddy currents in the case which tend to stop the motion of the needle.

The eddy currents circulating in solid conductors are converted directly into heat and are the source of much loss of energy and other derangements in dynamos, motors and transformers. To avoid them as far as possible, the solid conductor, as the iron core of an armature or induction coil, is made up of laminations, the plane of which is parallel to the lines of force of the field, See ¶ 332. Eddy currents circulate in the metallic bobbin of the D'Arsonval galvanometer coil when it moves in its magnetic field and tend to stop the motion according to Lenz's Law. It is for this reason that the Weston instruments are so dead-beat. The same action also takes place in the copper disc rotated between permanent magnets in the Thomson wattmeter.

Exp. 80: Strongly magnetise a bar electromagnet and strike one pole with a piece of flat sheet copper and you find a cushioning effect is produced. You are unable to strike the pole with as great force as when the current is off. Eddy currents are induced in the copper,

the reaction of the magnetic field of which tends to oppose the motion. The same is true if you try to quickly lift the sheet of copper from the pole.

Exp. 81: Suspend a copper penny by a thread between the poles of a horseshoe electromagnet. Twist the thread up and permit it to unwind. Send a current through the magnet and the motion of the penny ceases, due to the reaction of the eddy currents which stop it, but when the circuit is broken the thread carrying the penny continues to untwist.

Exp. 82: Excite an electromagnet from a source of alternating current. Hold a piece of sheet copper over one pole, and it is strongly repelled, and if held there against the repelling force it will get very warm. The moving alternating current field cuts the copper sheet and eddy currents are induced as before. If the electromagnet has a solid iron core it will also get quite hot for the same reason. The cores of alternating current electromagnets are made of bundles of wire to increase their resistance to the flow of eddy currents. The rapid magnetisation and demagnetisation of the iron core of an electromagnet by an alternating current also produces heat as a result of the molecular friction between the particles of the iron, ¶ 30. A certain amount of the electrical energy is converted into heat in this manner and is termed the *hysteresis* (hister-ee′-sis) *loss.*

Hysteresis may be defined as the molecular friction between particles of iron or steel when they are subjected to rapid changes in magnetisation. See ¶ 336.

293. Mutual Induction.—The induction due to two independent electric circuits reacting upon each other is called *mutual induction.* The previous examples of induction in a secondary circuit due to current flowing in the primary circuit illustrate mutual induction. Parallel conductors carrying independent alternating currents react upon each other by reason of the mutual inductive influence between them. Mutual induction in telephone circuits often gives rise to cross-talk unless the line is so constructed that the induction effects are neutralized, ¶ 299.

294. Self-Induction.—*Self-induction* is defined as the cutting of a wire by the lines of force of the current flowing through it. When a current begins to flow along a wire the magnetic whirls spring outward from the wire and cut it. This cutting of the wire by its own lines of force induces in it a momentary *inverse* E. M. F., or an E. M. F. which opposes the E. M. F. causing the current to flow, and is called a *counter E. M. F.* With a steady current the induction is only momentary, therefore a brief interval of time must elapse before the current passed through the circuit reaches its normal value. When the current flowing through the wire

is stopped, the magnetic field collapses, and in so doing again cuts the wire, but in the *opposite direction.* A momentary induced E. M. F. is set up which is now *direct*, or in the same direction as the E. M. F. which previously caused the current to flow. The effects of self-induction are therefore to oppose the starting of a current by reason of the inverse E. M. F. which must be overcome before the current can flow, and to momentarily *retard the cessation of the current* by reason of the direct induced E. M. F. when the circuit is broken. Momentary currents of self-induction are also produced in any circuit by any change in current strength through it, whereby the number of lines of force surrounding or interlinked with it is increased or decreased.

The effects of self-induction are scarcely noticeable in a straight wire carrying a current, but when it is coiled up, as in a helix the magnetic field of every turn cuts many adjacent turns and the E. M. F. is increased, being proportional to *the current, the number of turns and the magnetic lines through the coil.* When the coil contains an *iron core* the effects of self-induction are *very much greater.* One very noticeable effect is the *bright spark* appearing at the point of *breaking a circuit* containing wire wound around an iron core. No effect is noticed on closing such a circuit on account of the counter E. M. F., but at break a spark appears, due to the momentary induced direct current which tends to prolong the current in the circuit. The induced E. M. F. at break is very much higher than was the applied E. M. F. This induced current of self-induction is sometimes called the *extra current.* If the terminals at the point of break are held, one in each hand, and then separated, the body will receive a shock, the intensity of which will depend upon the size of the coil and the current used. No shock will be felt upon placing the hands across the battery, thereby indicating that the E. M. F. of self-induction is much higher than the battery E. M. F.

295. Gas Lighting Spark Coil.—The function of the spark coil used in electric gas lighting is to increase the self-induction of the circuit at break, as when the chain of a ratchet burner is pulled. A coil is inserted in series with the battery circuit and the burner, and the heat of the spark on breaking the circuit is sufficient to ignite the gas.

Such a coil, Fig. 278, consists of about 2 pounds of No. 16 insulated copper wire wound around an iron core 1 inch in diameter and 8

inches long. The core is not solid, but consists of a bundle of soft iron wires, which greatly increases the inductive action by diminishing the eddy currents, ¶ 292.

Exp. 83: Connect a galvanometer in parallel with a helix of fine wire, Fig. 279. Close the circuit and the needle is deflected, say to the right of zero, and the current divides between the galvanometer and the helix. Move the needle, by hand, to the zero position, and place some obstacle in the way so as to prevent it turning again to the right of zero. Now release the battery key and a momentary current, due to the self-induction of the helix, flows around the galvanometer needle, momentarily deflecting it in the opposite direction. The induced current through the helix, at break of circuit, is in the *same direction* as the battery current was, but flows in the opposite direction through the galvanometer connected to it. This is shown by the dotted arrow in the figure.

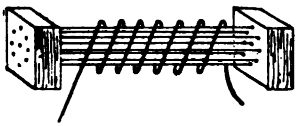

Fig. 278.—Gas Igniting Spark Coil with Laminated Core.

Exp. 84: In Fig. 279 an incandescent lamp is connected in shunt with an electromagnet and through the switch, K, to a battery of an E. M. F. equal to that required by the lamp. The resistance of the magnet should be such that with current flowing the lamp filament is just perceptibly red. At the instant of closing the switch the momentary self-induction of the electromagnet acts like resistance against the current, causing most of it to flow through the lamp, which glows brighter for a moment and then becomes dim as the current attains its steady value. On breaking the circuit the lamp again glows very brilliantly since it is in circuit with the electromagnet. The energy stored in the magnetic field is thus converted into a momentary direct current of a high E. M. F. and lights the lamp. The fields of a dynamo should not be broken when fully excited since the E. M. F. may become so high as to cause a puncture of the insulation at two or more points, and thus complete the circuit through the iron core, and cause a ground, ¶ 312. The self-induction at break of such a circuit is termed the *field discharge.*

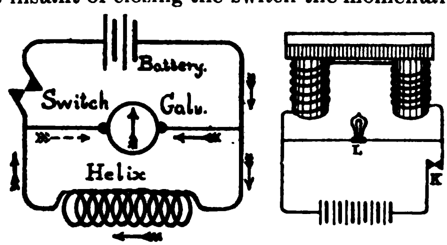

Fig. 279.—Experiments Illustrating the Extra Current of Self-Induction.

296. Inductance.—The cause of the self-induction is due to the property possessed by the wire or coil called *inductance,* just as the resistance of a wire is that property of it which opposes the flow of a current through it. A coil or wire, therefore, possesses inductance whether current is passing

through it or not. The amount of inductance offered by a coil depends on the number of turns of wire in the coil and on the magnetic conductivity of the medium surrounding it. A coil of 50 turns wound around an iron core has a very much higher inductance than a coil of 50 turns without an iron core. A coil of 15 turns wound on an iron core has less inductance than one of 60 turns wound on a similar core. The inductance of a coil or circuit is measured by the E. M. F. induced in it when the inducing current varies at any given rate. The unit of inductance is called the *henry* (the symbol for which is "L"), and is the induction produced in any circuit when the induced E. M. F. is one volt, and the current through the circuit varies at the rate of one ampere per second. The secondary coil of a 2-inch spark coil, ¶ 306, has an inductance of about 51 henrys; a 2.5 ohm electric bell, .012 henry or 12 millihenrys; the fields of a 3.5 K. W. 100-volt, shunt dynamo, 13 henrys.

297. Reactance and Impedance.—When an alternating current flows through a circuit containing inductance, the effects of self-induction will become continuous instead of momentary, and will considerably retard the flow of current through the circuit as long as it is maintained. The *apparent resistance* of a circuit to an alternating current is greater than the ohmic resistance. The cause of this apparent additional resistance is due to the effect of self-induction, and is termed *inductive resistance,* or reactance. Reactance is the effect of self-induction expressed in ohms. It, therefore, differs from inductance in that it exists only while the current flows. A coil has no reactance unless the current flows through it and the rate of flow is varied. This spurious resistance (reactance) in any circuit is measured in ohms, and is equal to the product of its inductance, the number of times the current flow is reversed per second and a constant (6.28). Ohm's Law, in its simplest form, is thus not applicable to calculations of circuits for alternating currents. The R in Ohm's Law for alternating currents is equal to the square root of the sum of the squares of the resistance and reactance ($\sqrt{R^2 + x^2}$). The total opposition offered to the flow of an alternating current by the resistance and the reactance is called the *impedance.* On account of the reactance, a larger size of conductor must be used in alternating current circuits than when direct currents are used.

298. Choke Coils.—

Exp. 85: In Fig. 280 a solenoid of several ohms resistance wound in the ordinary manner, is connected in series with an incandescent lamp and to a source of direct current (D. C.) by throwing the switch, S, down. The brilliancy of the lamp is practically the same with the solenoid in circuit as when it is cut out by the key, K. Neither is there any change in the lamp when an iron core is inserted in the coil. Now the circuit is connected to a source of alternating current (A. C.) by throwing S up. With the solenoid out of circuit the lamp burns as brilliantly as before, but when it is inserted, as by opening key, K, the lamp burns dimly. The current through it has been decreased by the self-induction of the solenoid. If an iron core is now gradually inserted in the coil, the current is gradually decreased, since the inductance is being increased, and the lamp may not give any illumination. The self-induction chokes back the current, so that less current is taken from the line. A device for regulating the candle power of lamps in an alternating current circuit is based on this principle, and is called a *choke coil.* The flow of alternating currents can thus be regulated much *more economically* than direct currents, since in the latter case regulation is effected by absorbing the energy in the extra resistance.

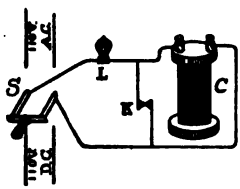

Fig. 280.—Effects of Self-Induction.

Exp. 86: The following measurements made on a coil of wire wound inductively when carrying a direct and alternating current will further illustrate the property of self-induction. In Fig. 281 the coil AB, without an iron core, is connected in series with an electrodynamometer and to a source of direct current. The pressure required to cause a known current to flow through the coil is 30 volts. The coil is then subjected to an alternating current pressure of such a value that the amperes through it, as indicated by the dynamometer are the same as before, and the potential difference across it is found to be 100 volts. A pressure of 100 volts alternating current is therefore required to send the same current through the coil as was maintained by 30 volts direct current. The difference in the two pressures is required to overcome the opposition due to the self-induction.

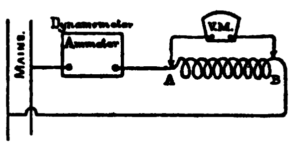

Fig. 281.—Effects of Self-Induction.

299. Neutralizing the Effects of Self-Induction—Inductive and Non-Inductive Circuits.

Self-induction in a coil may be neutralized by winding one-half of the coil in a right-hand direction and the remainder in the opposite direction. This is accomplished in practice by folding the length of wire to be used at its middle point and starting at this point, winding both halves as a single wire, when the termi-

nals will be conveniently arranged for connection. The magnetic effects of the current flowing in one direction neutralize those of the same current flowing in the opposite direction and the coil now offers practically the same resistance to either an alternating or direct current. Such a circuit is said to be *non-inductive* and contains practically no inductance, while an ordinarily wound coil constitutes an *inductive circuit.* No polarity would result from inserting an iron core in a non-inductively wound coil since the current through one-half of the turns would tend to magnetise one end with a **N**-pole,while in the other half the tendency would be to produce a **S**-pole at the same end.

The coils of laboratory rheostats and Wheatstone bridges are wound non-inductively, Fig. 126, so that they will have no magnetic influence on a galvanometer, and also so that the currents in the bridge arms may reach their maximum value simultaneously. Self-induction is neutralized in alternating current lighting and power circuits by placing the lead and return wires as close together as possible. For this reason *concentric cables* are used for such circuits. An incandescent lamp is practically a non-inductive resistance, while an electromagnet is an inductive resistance.

QUESTIONS.

1. The **N**-pole of a bar magnet is thrust through a key ring and quickly withdrawn without touching it ; the action is continued for a time and the ring becomes warm. How do you explain this ?

2. Is the direction of the induced current in question 1 clockwise or anti-clockwise, as viewed from the side next to you, when the bar magnet is withdrawn from the ring ? Make a sketch.

3. State three factors upon which the induced E. M. F. is dependent when conductors are moved through a magnetic field.

4. A cell connected to a galvanometer indicates 50 deflections. A portion of the connecting wire is coiled up and an electromagnet excited from another cell is plunged into the coil. The galvanometer needle momentarily indicates only 30°. Explain this and make sketch to illustrate your answer.

5. The two ends of a 5-pound reel of bell wire are connected to each other, and it requires more muscular force to quickly insert and remove an electromagnet from the centre of the reel than when the two ends are free. Explain fully. Make sketch.

6. The E. M. F. of a dynamo is too low and the field cores are fully saturated so that the voltage cannot be raised in this manner. How would you increase it and still use the same machine ?

7. Two sets of parallel independent circuits supply current to some incandescent lamps. At the instant of turning out all the lamps on

one set of mains the others burn more brightly. Explain fully and give detail sketch of the direction of currents in the circuits, etc.

8. An electromagnet is inserted in a coil of wire and the terminals of the latter then joined to a galvanometer but there is no momentary deflection of the needle. Explain why.

9. At the instant of breaking the electromagnet circuit in question 8 the needle is deflected 40°, while on making it again the deflections are only 35. Explain this and make sketch.

10. Two pieces of thick copper wire are joined to a battery, and when the ends are brought in contact and separated there is no perceptible spark. An electromagnet of high resistance is connected to the same battery and a bright spark appears when the circuit is broken. Since the E. M. F. of the battery is the same as before and the resistance so much higher than before, how do you account for the phenomenon?

11. A solid iron core electromagnet is excited by an alternating current. The core becomes very hot though the wire is sufficiently large to carry the current without becoming warm. State two reasons for the heating.

12. Using a copper mallet, why is it impossible to strike the pole of a strong electromagnet with as hard a blow as when the magnet is not excited?

13. State two phenomena occurring in the copper mallet when the pole of the electromagnet, in question 12, is struck.

14. Make a sketch of a copper disc rotating between two horseshoe permanent magnets, as in the Thomson recording wattmeter. Indicate polarities and directions of rotation and eddy currents.

15. Ten volts alternating current cause 5 amperes to flow through a straight insulated copper wire 20 feet long. The same wire is now coiled up and the current is only 3 amperes, yet the pressure and resistance of the wire are exactly the same as before. How do you explain this?

16. Why is a choke coil more economical than a rheostat?

17. The resistance of an electromagnet is 10 ohms but its apparent resistance to an alternating current is 15 ohms. What is meant by this expression?

LESSON XXV.

THE INDUCTION COIL.

Principle of the Induction Coil or Transformer—The Induction Coil—Action of the Coil—Action of the Condenser—Construction of Induction Coils—Wehnelt Electrolytic Interrupter—Table XIX. Sparking Distances in Air—Spark Coil Data—Table XX. Spark Coil Dimensions—Vacuum Tubes—Roentgen Rays (X-Rays)—The Fluorescing Screen and Fluoroscope—The Telephone—The Microphone Principle—The Blake Microphone Transmitter—The Telegraph—The Signal System and Circuits—Electric Waves—Wireless Telegraphy—Questions.

300. Principle of the Induction Coil or Transformer.—An induction coil, or transformer, consists of two independent coils in which, by induction, an alternating or interrupted electromotive force, maintained across one of the coils, is made to produce a higher or lower electromotive force in the other coil. Such a coil consists of three principal parts: the primary, the secondary, and the iron core. In Fig. 282 two independent coils are wound upon an iron ring. When the secondary is connected to a galvanometer and a current passed through the primary from a battery, the galvanometer needle will be momentarily deflected at "make" and "break" of primary, as in our previous experiments. The currents in the primary magnetise the iron core, and the lines of force in the core thread through the secondary coil producing induction effects. If the battery current is sent through the secondary, induction is produced in the primary as before. This simple ring form of closed iron circuit transformer represents the principle of construction in all induction coils or transformers. In Fig. 283 the iron circuit is of the open type and the primary wound upon an iron core, while the secondary is insulated from and wound on top of it. The induction is produced either

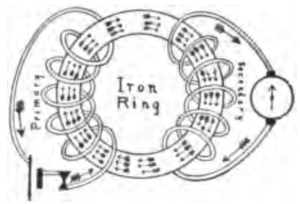

Fig. 282.—Closed Circuit Transformer.

by an interrupter in a direct current circuit or by an alternating current.

In all transformers the relation of the induced E. M. F. generated in the secondary circuit to that employed in the primary, is nearly proportional to the ratio of the number of turns in each circuit. For example, if the primary contains 100 turns and the secondary 2000 turns, then the induced E. M. F. will be about twenty times as great as that used in the primary. If this secondary contained only fifty turns then the E. M. F. would be only half as great as that in the primary. By a proper proportioning of the turns, then, any desired E. M. F. may be obtained from the secondary terminals.

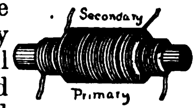

Fig. 283.—Open Circuit Transformer.

The function of an induction coil is to *transform the energy* delivered to its primary from any given voltage to a higher or lower voltage. While a current of low pressure may thus be transformed into one of a very high pressure, the latter loses in current what it gains in pressure, so that the watts in the secondary are no greater than those developed in the primary, but always a little less, owing to various losses in transformation and the I square R loss in the secondary circuit.

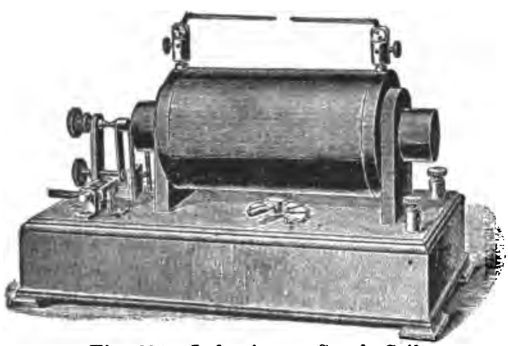

Fig. 284.—Induction or Spark Coil. For use with direct currents.

301. The Induction Coil.—The principle of the transformer is utilized in induction coils constructed to generate very high electromotive forces, capable of overcoming the resistance of the air and causing sparks to pass across air gaps. The induction coil, or *Rhumkorff's inductorium*, Fig. 284, is a *step-up-transformer* since, by induction, it raises the voltage of several cells connected to its primary to thousands of volts at the secondary terminals. It consists of a straight laminated core, made up of a bundle of soft charcoal iron wires

around which is wound the cylindrical primary coil, composed of several layers of heavy wire, while a secondary coil composed of thousands of turns of fine wire, is wound over the primary, similar to Fig. 283. The inner or primary coil is connected to a battery through an automatic interrupter, Fig. 285. At the "make" and the "break" of the primary circuit currents are induced in the secondary according to the laws of induction, ¶ 284, and appear as a series of sparks passing through the air from one secondary terminal to the other. The general appearance of such a coil is shown in Fig. 284, and its connections, in Fig. 285.

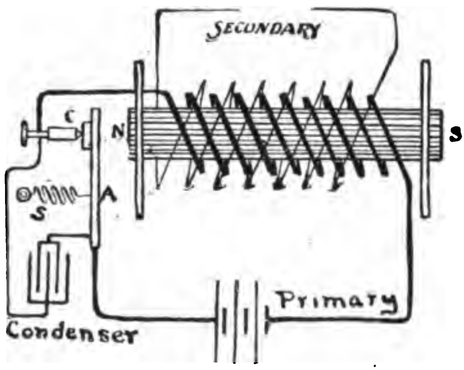

Fig. 285.—Diagram of Connections of a Spark Coil.

Exp. 87: The student's induction coil illustrated in Fig. 266, may be mounted on a base provided with a contact screw and vibrator arm, when induced currents can be produced automatically from the secondary coil. This arrangement is shown in Fig. 286, where the connections can be readily traced. Using the primary alone, the automatic action of the electric bell is illustrated. When short lengths of brass tubing are attached to the secondary terminals and then clasped, one in each hand, a peculiar muscular contraction is produced, due to the high voltage of the induced E. M. F. This is the physiological effect of an electric current, ¶ 96.

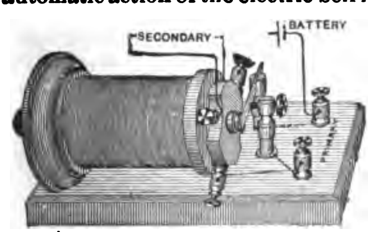

Fig. 286.—Student's Induction Coil as a Spark Coil.

302. Action of the Coil. The action of the automatic interrupter used on induction coils is shown in Fig. 285. The current from the battery flows through the soft iron pivoted armature, A, free to move, to the stationary contact post, C, the armature being held in contact with the point, C, by the spring, S. From C the current circulates around the primary core and returns to the battery. The contact screw ter-

minates in a piece of platinum wire and there is also a piece of sheet platinum fastened to the vibrator arm at the point of contact with the screw C. Platinum is used to prevent the oxidation due to the spark at the contact points. The instant the current flows through the primary coil it strongly magnetises the iron core, NS, which core attracts the armature by overcoming the tension of the spring. This breaks the primary circuit, the magnetism of the core ceases, and the spring pulls back the armature again "making" the circuit so that the same events are repeated. The armature vibrates continually as in an electric bell, and the circuit is "made" and "broken" thousands of times per minute. An *inverse* induced current in the secondary corresponds with each "*make*" of primary, while a "*direct*" current is induced on "*break*" of primary. Interrupted currents in the primary, therefore, produce alternating currents in the secondary.

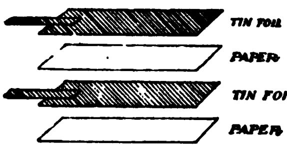

Fig. 287.—Detail of Condenser Construction.

The *self-induction* in the *primary circuit* has a very important bearing upon the action of the coil. At "make" of primary the counter E. M. F. opposes the battery current, and reduces the time rate of change of the current upon which the induced E. M. F. depends, while at "break," the self-induced current in the primary tends to prolong or increase the primary current, preventing its rapid fall to zero by sparking across the break. *A rapid rate of magnetisation and demagnetisation of the iron core means a great rate of change of the lines of force threading through the secondary coil, and hence a high E. M. F.* A *condenser*, ¶ 303, is added for the purpose of suppressing this spark across the primary break and of aiding the primary current to fall abruptly to zero.

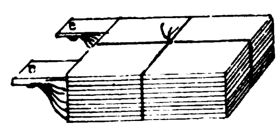

Fig. 288.—Plates of a Condenser Assembled and Connected.

303. Action of the Condenser.—A condenser for a spark coil consists of two sets of interlaid layers of tin-foil separated by sheets of paper coated with paraffin or shellac, Fig. 287.

The alternate layers of tin-foil are connected to each other, and two common terminals are thus formed, as depicted in

Fig. 288. There is no electrical connection between the condenser terminals, but if they are connected to a source of very high E. M. F. the plates become electrified or charged, and may be discharged when a proper path is afforded. The condenser is located in the base of the coil shown in Fig. 284, and its terminals connected across the primary break, points A and C of Fig. 285.

The condenser action is as follows: when current flows through the primary at "make," Fig. 285, no energy can be stored up in the condenser, but it appears as the magnetic field in the core and surrounding primary. At "break" the extra current of self-induction in the primary, instead of overcoming the resistance of the spark-gap, charges the condenser, and the core is more *quickly demagnetised.* At "break" also there is a complete discharge circuit for the condenser back through the battery and the primary coil, in the *opposite direction* to the *previous* primary current; the condenser thus aids in quickly demagnetising the iron core by tending to set up lines of force in the opposite direction. If the primary current is re-made before the *reverse condenser current* disappears, as is practically the case, the battery current has to first overcome this obstructing current before it can produce any effect. Thus the inductive effect of the "make" circuit is *retarded* by the condenser. With the use of a condenser then the E. M. F. of the "*direct*" secondary current at break is *exalted,* while that of the "*inverse*" secondary current on "*make*" is *diminished.* The consequence is that when the secondary discharge has to overcome much resistance only the former current is able to pass, and the secondary discharge *becomes practically an intermittent current of high voltage in one direction only.* In medical induction coils where no condenser is used the secondary charges are practically equal.

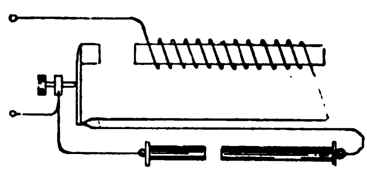

Fig. 289.—Primary Shock Coil.

The voltage generally applied to the primary of the ordinary induction coil varies from about 4 to 15 volts according to the size. A higher voltage causes excessive sparking and destruction of the platinum contacts. Specially constructed inde-

pendent vibrators are used with modern high class coils which can be connected directly to an electric light circuit of 110 volts or more. The vibrator is practically a relay, ¶ 313, which makes and breaks the current in the independent primary circuit by means of another pair of platinum contact points. This circuit can also be supplied from a 110-volt circuit and the current regulated by a rheostat.

304. Construction of Induction Coils.—Induction coils may be divided, according to their use, into two general classes, medical or therapeutic coils and spark coils. In the former, the winding is designed so as not to produce such a high E. M. F. as in a spark coil, and consequently no condenser is required. Some means for varying the intensity of the shock is provided, such as altering the number of turns in circuit in the secondary coil by a selector switch, or by so constructing the secondary that it may be gradually withdrawn from the primary. Regulation may also be effected by varying the position of a brass tube enclosing the iron core.

The tube screens the iron core from the action of the primary current, thereby weakening the magnetic field cutting the secondary circuit. Instead of magnetising the core, a portion of the energy of the primary circuit is thus expended in producing eddy currents in the tube. The iron core is composed of a bundle of soft charcoal iron wires, about No. 22 gauge. For medical coils the number of layers in the primary is generally from 4 to 6 and the size of wire used No. 24, 22, or 20, according to the dimensions of the coil, while the secondary is wound with No. 34 or 36. The primary will thus have considerable self-induction which is not a great disadvantage in these coils.

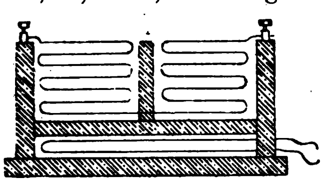

Fig. 290.—Sectional Winding of the Secondary of a Spark Coil.

Spark coils are usually rated according to the number of inches that the spark will jump between the secondary terminals through the air. Thus a two inch coil means that the E. M. F. is high enough to cause sparks to pass when the terminals are separated at a distance of two inches. The self-induction of the primary must be very low and so it is wound with about 2 layers of a much larger size wire than that used

in medical coils. The primary must be thoroughly insulated from the secondary, and also the coils of the secondary from each other when it is wound in sections. With insufficient insulation the induced E. M. F. is liable to cause a spark to pass from the secondary to the primary, or between sections of the secondary, instead of across the terminals. When the insulation is so punctured by the spark at two or more points the spark will always thereafter take the path of least resistance, in preference to that between the secondary terminals. When the coil is designed to produce a spark over 1.5 inches the secondary should be wound in a number of sections separated from each other by proper insulation. In Fig. 290, the secondary is wound in two sections as the potential difference between layers is less than when wound in a single coil. The sections must be so connected that the current will circulate through all of them in the same direction.

In Fig. 284 a commutating switch for reversing the current in the primary circuit, is mounted near the left-hand end of the base, thereby changing the polarity at the secondary terminals. Another selector switch near the centre of the base serves to connect more or less of the condenser's capacity across the points of "break." The following table gives the sparking distance and approximate corresponding E. M. F. between opposed sharp needle points:

Table XIX.—Sparking Distances in Air.

Volts.	Distance. (Inches.)	Volts.	Distance. (Inches.)
5000	.225	60000	4.65
10000	.47	70000	5.85
20000	1.00	80000	7.1
30000	1.625	100000	9.6
35000	2.00	130000	12.95
45000	2.95	150000	15.00

NOTE.—These values are correct for effective sinusoidal voltages.

305. Wehnelt Electrolytic Interrupter.—Instead of the electromagnetic vibrator previously described, the electrolytic effect of the current may be utilized to break the primary current of an induction coil. The Wehnelt interrupter consists of a vessel containing dilute sulphuric acid in which is immersed a lead plate and a glass tube having a small piece of platinum wire (about ¼ inch of No. 24)

sealed in its lower end. External connection is made with the platinum wire by filling the tube with mercury, or as in the electrode in Fig. 94. If this electrolytic cell be connected to a source of sufficient power so that 12 volts or more are maintained across it, with the *platinum as the anode** and the *lead plate* as the *cathode*, gases will be liberated by electrolysis. The oxygen gas enveloping the platinum tip practically insulates it from the solution, and the circuit is interrupted when the evolution of gas ceases and the circuit is again "made." The action is very rapid, and the "makes" and "breaks" quick and sharp. The cell emits a buzzing noise and a yellowish light surrounds the platinum wire. A Wehnelt interrupter connected in series with the primary of a small spark coil will cause it to give a much larger spark than when the mechanical interrupter is used. The frequency of the interrupter depends upon the area of platinum exposed, the self-induction of the coil and the voltage. This interrupter in series with the primary coil may be operated from 110 volts.

Prob. 116: The primary of an induction coil is wound with 100 turns of No. 14 copper wire and the secondary, with 35,000 turns. Ten volts cause a current to flow through the primary. What is the approximate E. M. F. at the secondary terminals?

By ¶ 300, $\frac{35000}{100} = 350$, or there are 350 times as many turns on the secondary as on the primary.

$$10 \times 350 = 3500 \text{ volts, secondary.}$$

$$E = 10 \text{ volts in primary, ratio of transformation} = 350.$$

Prob. 117: The resistance of the primary in Prob. 116 is 0.5 ohm, and if the loss in conversion of the energy to the higher potential is 50 per cent what will be the approximate current strength in the secondary circuit?

By Formula (28) $I = \frac{E}{R} = \frac{10}{.5} = 20$ amperes in primary.

By Formula (62) $W = E \times I = 10 \times 20 = 200$ watts in primary.

50% of 200 watts = 100 watts in secondary.

By Formula (63) $I = \frac{W}{E} = \frac{100}{3500} = .028$ ampere.

NOTE.—The above problem is only approximate, since other factors enter into the calculation. It should assist, however, in understanding the relation between the expended primary energy and that appearing as a high potential spark in the secondary.

306. Spark Coil Data.—The following dimensions are given for several sizes of spark coils, similar to that depicted in Fig. 284, so that the student may be guided if he attempts construction.†

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* If the platinum wire be connected by mistake as the cathode, it will be melted. See ¶ 264.

† In a book entitled *Induction Coils and Coil Making*, by Allsop, will be found complete data for constructing and operating spark coils. The data for a 12 inch coil as given, requires 12 pounds of No. 36 silk covered wire, or about five miles in length.

Table XX.—Spark Coil Dimensions.

Length of spark.	$\frac{3}{8}$ inch	$\frac{1}{2}$ inch	1 inch	2 inches
Size of bobbin ends	$2\frac{1}{8} \times 1\frac{1}{4}$	$2\frac{1}{2} \times \frac{5}{16}$	$3 \times \frac{5}{8}$	$4 \times 2\frac{3}{4} \times \frac{3}{8}$
Length of bobbin	4	$5\frac{1}{2}$	$6\frac{1}{2}$	$6\frac{1}{2}$
Length and diameter of core.	$4\frac{1}{2} \times \frac{7}{16}$	$6 \times \frac{5}{8}$	$6\frac{1}{2} \times \frac{3}{4}$	—
Size of base . .	$7\frac{1}{4} \times 3\frac{1}{4} \times 1\frac{1}{2}$	$9 \times 5 \times 2$	$14\frac{1}{2} \times 6 \times 1\frac{3}{4}$	$12 \times 7\frac{1}{2} \times 3\frac{1}{4}$
Size of tinfoil sheets . . .	4×2	$5\frac{1}{2} \times 3\frac{1}{4}$	6×4	6×6
Number of tinfoil sheets . .	36	40	40	60
Size of paper sheets	5×3	$6\frac{1}{2} \times 4\frac{1}{4}$	9×5	—
Primary coil . .	No. 18	No. 18	2 layers No. 16, silk covered.	2 layers 14 B. W. G. silk covered.
Secondary coil	$\frac{3}{4}$ lb. No. 40	1 lb. No. 40	$1\frac{1}{4}$ lbs. No. 38	$2\frac{1}{2}$ lbs. No. 36

Two large induction coils, capable of giving a 45-inch spark between their secondary terminals, and weighing 1500 pounds each, were recently constructed by an American firm for the Japanese government. The primary interrupter was actuated by a small motor and the rate of interruptions was capable of being varied between wide limits. With 40 volts maintained across the primary circuit, a current of 30 amperes produced a very heavy 42-inch spark.

Exp. 88: The *mechanical effect* of the spark from an induction coil may be observed by holding a piece of cardboard between the terminals when the spark is passing. The card will be perforated, leaving a bur on each side. Thin plates of any non-conductor can be punctured in like manner.

Exp. 89: To observe the *heating effect*, place a small quantity of gunpowder on a glass plate and arrange the terminals of the coil so that the spark will pass through it. On closing the battery circuit, the heat developed by the spark causes the powder to explode.

Exp. 90: The *chemical effect* is illustrated by moistening a piece of blotting paper with the solution used in the polarity indicator, ¶ 106. Attach one of the secondary terminals to the edge of the paper, hold the other in the hand by an insulator, and trace designs on the paper when the coil is in action. The discharge decomposes the chemical salt, as shown by the blue mark. The action is the same as given in ¶ 106.

307. Vacuum Tubes.—Vacuum tubes, first devised by Geissler, are thin glass tubes, variously shaped and provided

with a platinum connection at each end of the tube, which extends a short distance into it. The tubes are then partially exhausted and filled with either a gas, liquid, or solid, and sealed up. On connecting the terminals to the secondary of a spark coil, and starting the coil in action, a beautiful discharge takes place, filling the tube with a luminous glow. The fluorescent effect depends upon the material introduced into the tube. The electric spark will not pass through a vacuum. The high potential maintained across the tube causes the molecules of gas to become positively and negatively electrified, and the resulting attractions and repulsions which occur produce a violent molecular bombardment, causing the fluorescent effect.

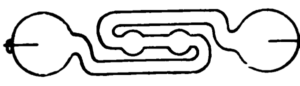


Fig. 291.—Geissler Tube.

308. Roentgen Rays (X-Rays).—While experimenting with a vacuum tube, excited from an induction coil, William Roentgen, of Germany, discovered that a sensitized photographic plate, concealed from daylight, but lying near the vacuum tube, indicated exposure to light when developed. Upon further investigation he found that a light was emitted from the vacuum tube, not perceptible to the human eye, but capable of penetrating many substances, as wood, metal, paper, etc. When different substances are interposed between a protected sensitized plate and an excited vacuum tube,

Fig. 292.—Radiograph of the Human Foot in a Shoe. Made by Roentgen rays.

capable of producing rays of this light, it penetrates them with different intensities, according to their density, so that the sensitized plate, upon development, shows the shadows of the objects interposed. A photographic print made from such a negative is termed a *radiograph.* When the human hand is placed between the protected plate and the tube the plate is scarcely affected directly underneath the bones, because they are nearly opaque. Considerable light penetrates the flesh and affects portions of the plate directly underneath it. A print made from such a negative gives shadows of the bones and a faint outline of the flesh. The shadows of the bones in all animal bodies can thus be made, and broken bones and foreign objects, such as bullets, needles, etc., accurately located.

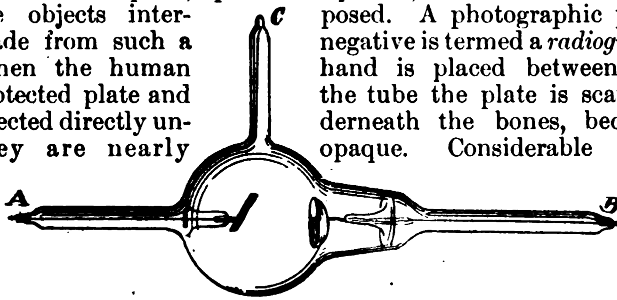


Fig. 293.—Focus Tube for X-Ray Work.

Fig. 294.—Examining the Bones of the Hand by the Fluoroscope.

A radiograph of the human foot in a shoe is illustrated in Fig. 292. The nails of the shoe, etc., as well as the bones of the foot, are clearly discernible. Professor Roentgen first called the rays of this peculiar light X-Rays, but they are usually named in his honor, Roentgen rays. A common form of tube used in X-ray work, called a focus tube, is illustrated in Fig. 293. A concave aluminum reflector extends a short distance inside the glass tube and a wire attached thereto terminates at point B. This reflector is connected to the

negative pole of the induction coil and forms the cathode o. the tube. The anode is a piece of sheet platinum inclined at about 40° to the axis of the tube, similarly connected to the positive pole of the induction coil at point A. The tube is exhausted to a fairly high vacuum and the X-rays emanate from the tube below the platinum anode.

309. The Fluorescing Screen and Fluoroscope.—A piece of paper or board coated with certain crystals, as platino-barium cyanide, or tungstate of calcium, and placed near a fluorescing vacuum tube in a darkened room, becomes a *fluorescent screen*, whether it be looked at from the crystal coated or the opposite side. The light is of a pale greenish yellow cast. If the hand be interposed between such a screen and the tube, the shadow of the bones can be plainly seen on the screen, the bones intercepting some of the Roentgen rays, and thus causing the shadow. Wood readily allows the rays to pass through it, so that if an inch board be held between the hand and the screen, the shadow is still visible. In the fluoroscope such a fluorescing screen forms the bottom of a box, the opaque sides of which slant inward toward the top where an opening is left for observation, Fig. 294. The daylight is thus excluded and the shadows of objects interposed between the fluoroscope and the tube are plainly visible upon the enclosed fluorescing screen. Fig. 294 illustrates the manner of viewing the bones of the hand. The tube is not generally enclosed, however, as shown in the cut.

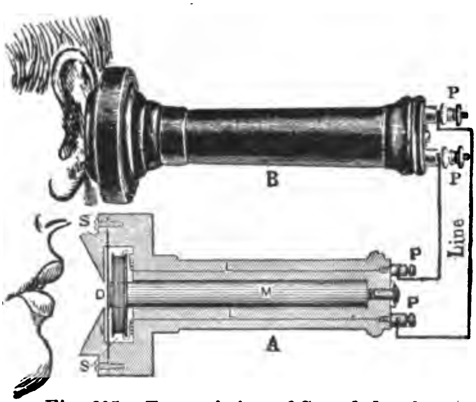


Fig. 295.—Transmission of Speech by the Bell Telephone.
The transmitter and receiver are exactly alike.

310. The Telephone.—An instrument designed for the transmission of articulate speech by an electric current is called a telephone. A section and perspective view of a *Bell telephone* is shown in Fig. 295. A

small spool of fine wire encircles one end of a bar magnet mounted in a rubber tube, the ends of this coil being carried to the far end of the tube and connected to the binding posts, PP. A thin circular iron diaphragm is located very close to the pole of the magnet, at the coil end, and is supported by a conical-shaped piece of rubber, attached to the tube, which serves either as a mouthpiece or ear trumpet. When two such instruments are connected by wires, as in Fig. 295, either one may be used as a transmitter and the other as a receiver. No battery is required.

When a person talks to the disc of the transmitter, A, the sound waves striking it cause it to vibrate. The disc is magnetised by induction from the magnet's pole, and as it vibrates the number of lines of force threading through the coil are constantly being increased and decreased as the disc approaches and recedes from the coil. Alternating induced currents are thus set up in the coil, which currents flow through the line to the coil of the receiver at B. When the direction of the arriving current is such as to reinforce the magnetism of the receiver's magnet its disc is strongly attracted, and when the current produces a demagnetising effect the disc flies back. The disc of the receiving telephone is thus compelled to repeat every movement of the disc in the transmitter, and the vibrations of the receiver produce sound in the same manner as the vibrations of a drum. This telephone transmitter is practically an alternating current dynamo, driven by the energy of the human voice, while the receiver is a motor driven by the current from the generator.

Fig. 296.—Apparatus to Illustrate the Principle of the Microphone.

311. The Microphone Principle.—A microphone is a device for rendering faint or distant sounds distinctly audible, and is used in many telephone transmitters, ¶ 312. The principle involved is the production of an unsteady electric current by a variable resistance introduced into the circuit. A simple form is illustrated in Fig. 296. A and B

are two carbon buttons one of which is fastened to a thin pine wood sounding board and the other to a brass spring, S, which causes B to touch A. The buttons are connected in circuit with a telephone and battery. While the current is flowing the least motion, caused by sound waves or other means, will vary the contact resistance between the buttons, and thus vary the current strength in the telephone circuit. The induced currents in the telephone cause the disc to reproduce the original sounds. The telephone may be located at a considerable distance from the microphone, when the reproduced sound, as the ticking of a watch, will be as audible as though produced close to the ear.

312. The Blake Microphone Transmitter. — The induced electric currents set up by the human voice in the Bell

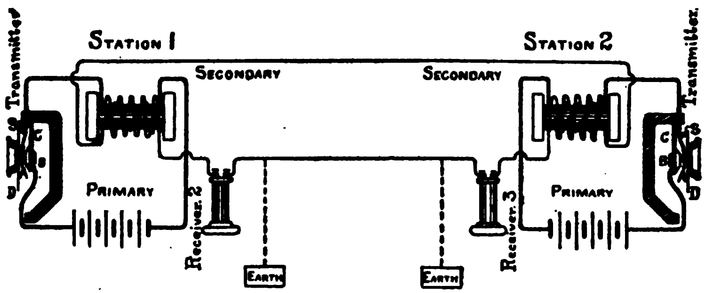


Fig. 297.—Connections of a Telephone System for Two Stations.
Blake microphones are used as transmitters and Bell telephones as receivers.

telephone, become materially weakened when they have to flow over lines of considerable length and resistance, so that the sounds in many cases become inaudible. In commercial telephone systems the Bell telephone is used as a receiver only, the microphone principle being used in the construction of the transmitter, so that the sound of the voice is only required to regulate or vary an electric current already generated by a battery, instead of being used to generate the current. The general arrangement of two telephone stations will be understood from Fig. 297. Each transmitter is a microphone, in which the spring, S, supports a small carbon button, A, against which rests the hammer shaped end, B, of another spring, C. The springs are insulated from each

other, and are connected in series with a battery circuit and the primary of a small induction coil.

Sound waves cause a vibration of the diaphragm, D, and the varying pressure it exerts between the carbon button and the hammer, causes variations in the battery circuit, as in the microphone. The induced secondary current flows through the receiver of station No. 1, and through the line to the Bell receiver and the secondary coil at station No. 2, causing the diaphragm of the receiver to vibrate in unison with that of the transmitter and so produce articulate speech. One wire from each receiver, as at points 2 and 3, may be connected directly to the earth through a gas or water pipe and a saving in copper effected by using only one transmission line. The system would then be working on a *ground return*, the earth acting as the other conductor. A *ground* is the contact of a conductor in any circuit with the earth, permitting an escape of current if another ground exists.

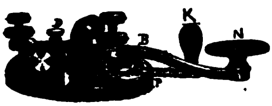


Fig. 298.—Telegraph Transmitting Key.

313. The Telegraph.—The telegraph instrument is an apparatus for transmitting signals by the aid of an electric current. It consists of the *line, the transmitter or key, the receiver or sounder, the relay and the battery.* The line between two stations is generally a single iron wire with a ground return. The *transmitter key* is depicted in Fig. 298. It consists of a brass lever with its axis pivoted at AA, carrying a platinum contact point, B, which is brought into contact by depressing the knob against the action of the spring, S. On depressing the lever by the knob, N, the two platinum points, B, P, connected to the line by posts C and D, are brought into contact and complete the circuit. When not in use the circuit is closed by the switch, K. The *sounder*, Fig. 299, consists of a brass lever with its axis pivoted at C, and carries an iron armature, A, of the

Fig. 299.—Telegraph Sounder.

electromagnet, M, which is connected in circuit by two binding posts, P, P. A clicking sound is produced at each "make" of the circuit and a spring pulls the armature back on "break" of circuit. In long lines the current, due to the high resistance, may be so small as to render the clicks of the sounder inaudible, when a relay is used. A *relay*, Fig. 300, is a small switch operated by an electromagnet wound with many turns of fine wire. The magnet, M, is inserted in the main circuit by the posts, 3 and 4, and the platinum contact points, S, S, are brought in contact when the armature, L, of the magnet is attracted against the action of the spring, B. This switch, S, S, is inserted in a local circuit with a battery and sounder by the posts, 1 and 2, Thus a very weak current through the relay brings into action a strong local current which operates the sounder.

314. The Signal System and Circuits.—A series of armature clicks separated by intervals of long or short duration constitute the signals transmitted. A short interval between clicks is called a "dot," and a longer interval a "dash." By different combinations of the "dashes" and "dots" an alphabet is constructed and words spelled from the signals received. The alphabet devised by *Morse* is generally used. Low voltage dynamos or closed circuit batteries are used for operating telegraph systems.

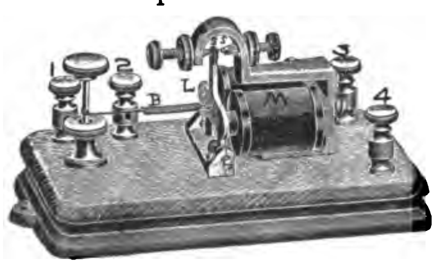


Fig. 300.—Telegraph Relay.

Connections for three stations provided with relays and local circuits are given in Fig. 301. When one of the stations signals to another the third also receives the signal, since all the relays are in series. The function of the small cut-out switch on the transmitter key is to preserve the continuity of the line since it is in series with it, as shown in Fig. 301.

315. Electric Waves.—The magnetic field surrounding a conductor through which a current is flowing changes for each change in current strength. When the current strength increases, the magnetic field around the conductor enlarges

or expands outward in all directions, but with a decrease in current strength, the field returns again toward the conductor. If instead of a slowly increasing and decreasing current in any circuit we consider electric oscillations of very high rapidity, as the discharge of an induction coil, then part of the energy of the magnetic field is radiated off into space in all directions as electromagnetic waves corresponding to the ripples on the surface of a pond when a stone is thrown into it. Only a portion of the energy of the magnetic field returns again to the circuit. Electricity travels at the rate of 186,400 miles per second, and these waves are also propagated

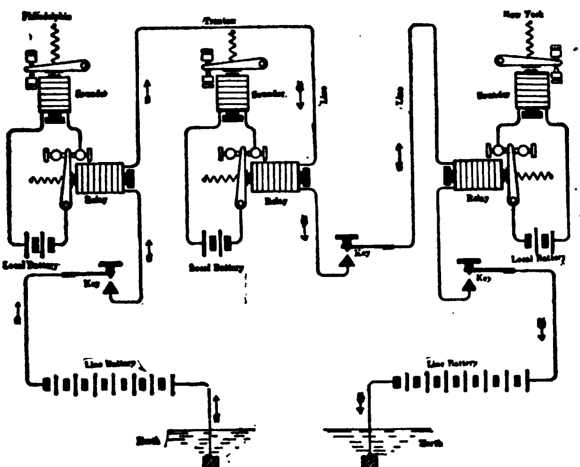


Fig. 301.—Connections for Three Telegraph Stations Using Relays.
One transmitting wire is used and a ground return.

at this speed. There are also about 230 million waves radiated per second. To propagate these waves with the best results from an induction coil, the secondary terminals are connected to brass spheres, between which the discharge occurs.

316. Wireless Telegraphy.—In wireless telegraphy signals are transmitted through space by electric waves. These waves are not obstructed by trees, houses, hills, fog, etc., and may be transmitted on land or across water. The system requires a *transmitter* and a *receiver*. The transmitter is gen-

erally an induction coil capable of giving from a 3 to a 6-inch spark between brass spherical terminals, the spark gap being regulated to obtain the best results for any given conditions. One terminal of the secondary is also connected to a vertical wire or "mast," which assists in the propagation of the waves while the other terminal is grounded, Fig. 302. A telegraph key, Fig. 298, is introduced into the primary circuit of the induction coil, whereby the "dot" and "dash" system of signals may be used. Details of the *receiving apparatus* are shown in Fig 302. A small glass tube (say $\frac{1}{8}$ inch inside diameter) contains two plugs of silver, separated from each other by a small gap (about .04 inch), which space is *partially* filled with a mixture of silver and nickel filings, and forms what is called the *coherer*. The plugs are connected in

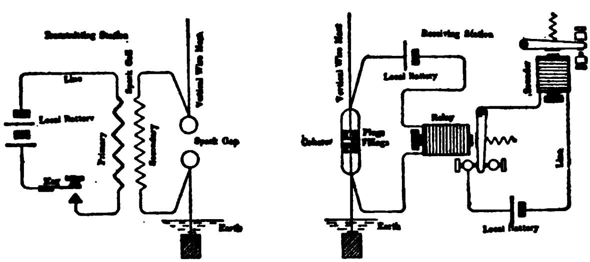


Fig. 302.—Connections of Transmitting and Receiving Stations for the Wireless System of Telegraphy.

The stations may be located miles apart with no metallic connections between them.

circuit with a battery and a relay of several hundred ohms resistance. One plug is also connected to a *vertical receiving mast*, and the other to the ground. The relay is made to close a local circuit containing a battery and telegraph sounder, Fig. 299. Owing to poor contact between the silver plugs and the filings the resistance of the coherer may be 1000 ohms or more, so that the battery cannot send sufficient current through it to operate the relay, When the coherer is struck by an electromagnetic wave, propagated from the distant spark coil, just as a chip floating on a pond would be struck by a ripple, the filings *cohere* and lower the resistance of the coherer to about 5 ohms. The battery now sends a current through it which operates the relay, and the signal transmitted is reproduced by the sounder. If the coherer be

gently tapped the filings will *decohere*, and their resistance become as high as before. This can be automatically accomplished by locating the coherer tube near the sounder armature, so that in reproducing the signal it taps the tube, and thus "decoheres" it after each signal. Signor Marconi, who first perfected the system, uses an exhausted coherer tube with sealed-in electrodes, this being more sensitive, as the particles do not become oxidized. Telegraphic communication by wireless telegraphy has been established between ships at sea and the mainland for a distance of more than one hundred miles. The ship and the shore station were equipped with duplicate transmitting and receiving instruments.

QUESTIONS.

1. How does an induction coil differ from a primary battery?
2. What is the difference between the current flowing from a battery and that from the secondary of an induction coil?
3. The primary of an induction coil is wound with 480 turns of wire and the secondary, with 80 turns. If 1200 volts are maintained across the primary terminals, what will be the relative voltage across the secondary terminals?
4. An interrupted current in the primary of an induction coil produces an alternating current in the secondary circuit. Explain fully how one secondary terminal can then be called a cathode and the other an anode.
5. Make a complete sketch of an induction coil with condenser, and indicate the directions of current in primary and secondary circuits at "make" and at "break."
6. What is the advantage of using a condenser with an induction coil?
7. What is the objection to using a solid iron core in the construction of an induction coil?
8. Make sketch of Wehnelt interrupter connected to an induction coil. Indicate direction of currents.
9. What is a fluorescing screen and how is it used for practical purposes?
10. Explain the principle of action in a simple telephone transmitter.
11. What is a microphone?
12. What advantage does a microphone transmitter possess over that of a simple type of transmitter?
13. Make complete sketch of a transmitting and receiving telephone station using Blake microphone transmitters.

LESSON XXVI.

DYNAMO ELECTRIC MACHINES.

The Dynamo—Classification of Dynamos—A Simple Dynamo—Alternating Current Dynamo—Graphic Representation of an Alternating Current—Magneto Alternator—Simple Direct Current Dynamo—Graphic Representation of a Direct Current—Multi-Coil Armatures—Gramme Ring Armature—Induced E. M. F. in a Ring Armature—Siemens Drum Armature—Advantages of Drum and Ring Armatures—Drum-Wound Ring Armatures—Open Coil Armatures—Questions.

317. The Dynamo.—The dynamo is a machine for converting mechanical energy into electrical energy by means of electromagnetic induction. A dynamo does not create electricity, but generates or produces an induced electromotive force, which causes a current to flow through a properly insulated system of electrical conductors external to it. The amount of electricity obtainable from such a generator is dependent upon the mechanical energy supplied. In the circuit *external* to a dynamo the E. M. F. causes the electricity to flow from a higher or positive potential to a lower or negative potential, just as water flows from a higher to a lower level. In the *internal circuit* of a dynamo the E. M. F. causes the current to flow from a lower potential to a higher potential, just as water is pumped or forced from a lower to a higher level. The action of a dynamo is based upon

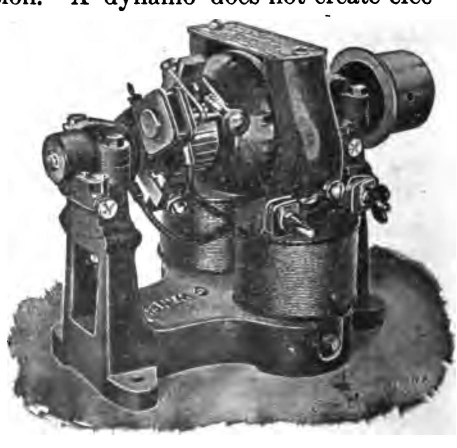


Fig. 303.—Bipolar Dynamo or Motor.

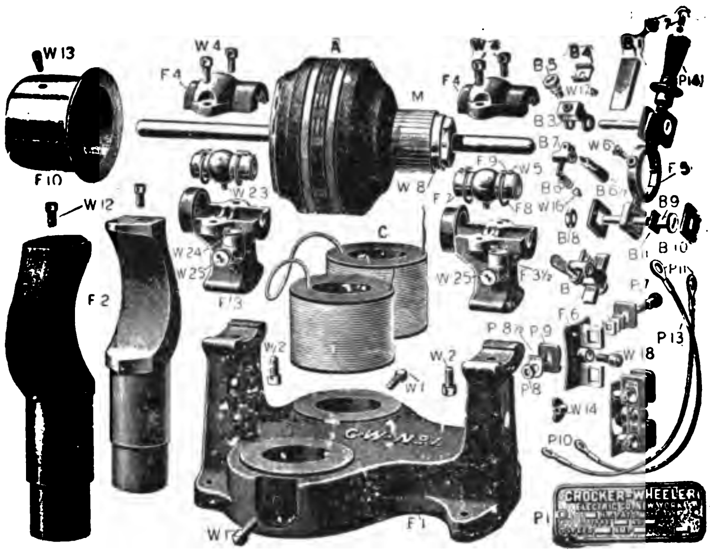


Fig. 304.—Dissected Bipolar Dynamo.

LIST OF PARTS.

F-Frame. A-Armature. C-Commutator. C-Field coil complete. P-Part. B-Brush. W-Screws.

FRAME-F.	Part.
Base,	**F 1**
Field magnet,	**F 2**
Pillow blk., lower part,	**F 3**
Pillow blk., lower part comm. end,	**F 3½**
Pillow blk., cap,	**F 4**
Rocker arm,	**F 5**
Binding post saddle,	**F 6**
Journal box,	**F 7**
Oil rings	**F 8**
Oil rings retaining lips,	**F 9**
Pulley,	**F 10**
Armature, complete,	**A**
Commutator, complete,	**M**
Field coils, complete,	**C**

PARTS-P.	Part.
Name-plate,	**P 1**
B. posts studs,	**P 7**
" " nuts,	**P 8**
" labels.	**P 8½**
" insulation,	**P 9**
" cable tips,	**P 10**
Rocker arm cable tips,	**P 11**
Flexible cables,	**P 13**
Rocker arm handle,	**P 14**
BRUSHES-B.	
Brush holder	**B**
Brushes,	**B 1**
Brush holder,	**B 4**
" " pressure plate,	**B 4**
Brush holder thumb-screw,	**B 5**
Brush holder springs,	**B 6**
" " spring tightener screw,	**B 6½**
Brush holder collars,	**B 7**
" " rod nuts,	**B 8**
" " rod,	**B 9**

PARTS-P.	Part.
Brush holder rod insulation,	**B 10**
SCREWS-W.	
Field to base,	**W 1**
Pillow blk. to base,	**W 2**
Cap to pillow blk.,	**W 3**
Oil ring lip,	**W 5**
Rocker arm set screws,	**W 6**
Rocker arm handle,	**W 7**
Comm. set screws,	**W 8**
Name-plate to field,	**W 12**
Pulley set screws,	**W 13**
Wing nuts,	**W 14**
Brush spring to holder,	**W 16**
" pressure plate to holder,	**W 17**
Saddle to field,	**W 18**
Screw pin in journal box,	**W 23**
Oil chamber cover,	**W 24**
" " stopper screw.	**W 25**

the principles of electromagnetic induction, discovered by Faraday, and fully considered in Lesson XXIV.

The dynamo consists essentially of two parts: a *magnetic field*, produced by electromagnets, and a number of loops or coils of wire wound upon an iron core, forming the *armature*, and so arranged that the number of the magnetic lines of force of the field threading through these coils will be constantly varied, thereby producing a continuous E. M. F.

318. Classification of Dynamos.—According to their mechanical arrangement, dynamos may be divided into three classes:

1. *A stationary field magnet and a revolving armature,*
2. *A stationary armature and a revolving field magnet,*
3. *A stationary armature and a stationary field magnet, between which is revolved an iron core.*

In the first class provision is made for conducting the current from the armature either by collector rings, ¶320, or by a commutator, ¶323. In the second class provision is made for conducting the current to the revolving field by collector rings, while in the third class there are no moving wires nor contacts. Dynamos may be further classified according to their design and mechanical construction into,

1. *Direct current machines,*
2. *Alternating current machines, or alternators.*

In direct current dynamos the field magnets are usually stationary while the armature revolves; in alternators, the armature is usually stationary while the field magnets revolve, while in some types both are stationary while an iron core is revolved. All dynamos are practically alternators—that is, machines in which alternating currents are generated. When provided with a suitable commutator, ¶ 323, the current is made direct in the external circuit, but still alternates in the machine.

319. A Simple Dynamo.—Consider the single closed loop of wire, ABCD, Figs. 305 and 306, which is mounted on a shaft and may be rotated around its horizontal axis in the uniform magnetic field, NS, in the direction of the arrow. The direction and variation in magnitude of the induced E. M. F. is the same as that given under Faraday's Law for the different positions of a loop during a complete revolution in Fig.

274 and ¶ 291.* At the position ABCD, Fig 306, there is no induced E. M. F. in the loop, since all the lines of force of the field thread through it. During the first quarter of a revolution, the lines of force threading through the loop are gradually diminished at an increasing rate, and the E. M. F., *depending on the rate of change of the lines of force* through it, increases in magnitude with its direction from b to a in the right-hand side of the loop, and from c to d in the left-hand side. At the position of one-quarter revolution, indicated by abcd, the plane of the loop is parallel to the lines of force so that none thread through it, and the arrows indicate the direction of the current. The rate of change is now a maximum as is also the E. M. F.

Fig. 305.—Generation of an E. M. F. by the Rotation of Rectangular Coils of Wire in a Magnetic Field.

The field magnets are excited from a source of current and the terminals of the coil are connected by brushes and lead wires to a voltmeter.

During the second quarter of the revolution the lines of force thread through the opposite side, which is equivalent to a further diminution of the lines of force through it, the rate of change and the E. M. F. decreasing until at half revolution the E. M. F. is zero. The direction of the E. M. F. is the same throughout this half revolution, and the current flows around the loop from a to c, to d, to b, to a, changing in strength with every variation of the generated E. M. F. During the next half revolution the same variations in E. M. F. occur but the induced E. M. F. is in the opposite direction. The current is therefore reversed *twice in every revolution*, or an *alternating current flows around the loop.*

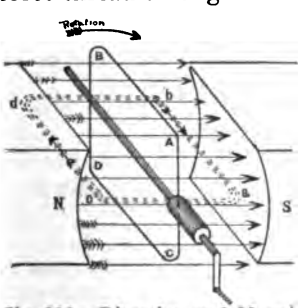


Fig. 306.—Direction and Magnitude of the Induced E. M. F. in a Dynamo.

* The student is advised to read again ¶ 291 which fully explains the fundamental principle of the dynamo.

22

320. Alternating Current Dynamo.—To utilize the current flowing in the above closed loop when it is rotated in the magnetic field, some mechanical device must be used to lead or collect the current from the rotating loop so that it will flow through a circuit external to it. Two collector rings are used for this purpose and consist of rings of copper mounted on a wooden or hard rubber hub, Fig. 307, this being mounted on the shaft with the loop. The rings *are insulated from each other and from the shaft.* The terminals of the loop are connected, one to each ring, and stationary strips of copper, P and M, termed *brushes*, rest upon the rings and are connected to the external circuit. When the loop is revolved a sliding or wiping contact is thus established and the current is conducted to the *external circuit.*

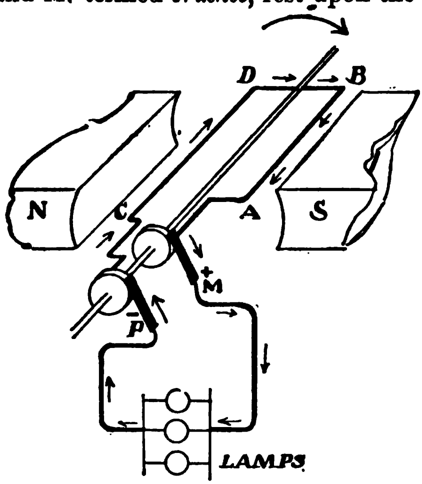


Fig. 307.—Simple Alternating Current Dynamo. At the instant depicted in the revolution brush M is positive.

During the first half revolution of the loop, ABCD, Fig. 307, the direction of current in AB is from B toward A, and *from brush, M, which is therefore positive* to the external circuit, composed of incandescent lamps in parallel. From the lamp terminals the current flows back to *brush P*, the *negative brush*, and around the loop from C to D, to B, etc. Now consider the second half revolution, Fig. 308. The direction of current in the wires AB, and CD, is reversed, Fleming's rule, and current flows from D to C, through *brush P, now positive*, then through the lamps in the opposite direction to that in Fig. 307, and through *brush M, now negative*, to AB, to D, etc. In every revolution the polarity of the brushes changes twice, or there are *two alternations of current per revolution in the external circuit.* The number of alternations per minute in any alternator equals the *speed in revolutions per minute mul-*

tiplied by the number of poles. The number of times which the alternations occur is sometimes expressed as the *frequency*, a frequency of 7200 meaning 7200 reversals of current per minute. In practice the *frequency* is expressed for the period of one second, and termed the *cycles*, ¶ 393.

Student's Experimental Dynamo and Motor.—A simple apparatus for studying the principles of induction and commutation in a dynamo, is illustrated in Fig. 309, and consists of a horseshoe electromagnet fitted with cast-iron pole pieces and mounted on a wooden base. A rectangular coil of No. 26 copper wire is mounted on a hardwood shaft, provided with pointed steel ends and suspended between two brass V centres, suitably supported by a brass framework extending from the pole pieces. The framework also carries two insulated brush holders. At one end of the shaft the coil terminals are connected to a pair of collector rings mounted upon it, while the same terminals are also connected to a two-part commutator at the other end of the shaft. By reversing the position of the coil between the pole pieces the brushes will rest either upon the rings or upon the commutator. The electromagnets have a resistance of 1.3 ohms each and are to be excited from a source of current. The brushes may be connected to a detector galvanometer, and when the shaft is rotated by hand either the alternating or direct current may be studied. The resistance of the rectangular coil is 5 ohms. When connected as a shunt motor the rectangular coil will make several hundred revolutions with an applied E. M. F. of 4 volts.

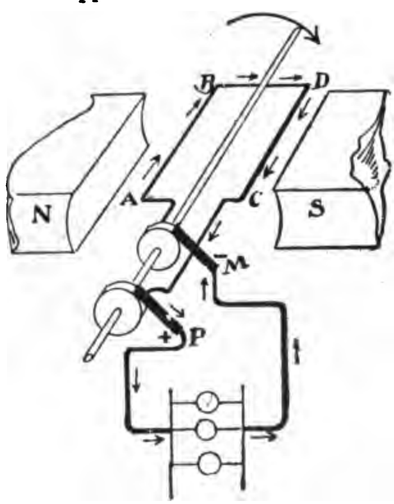


Fig. 308.—Simple Alternating Current Dynamo.

Direction of current in the coil at one-half revolution from the position in Fig. 307. Brush M is *now* negative.

Exp. 91: Separately excite the magnets (connected in series) of the student's experimental dynamo, Fig. 309, so that one pole piece will be **N** and the other **S**, and adjust the brushes so that they will bear lightly upon the *collector rings*. Connect the brushes to the detector galvanometer, Fig. 153.

(a) Revolve the shaft slowly and note the alternating deflection of the galvanometer needle.

(b) Increase the speed and note that the needle remains at zero with a perceptible vibration.

(c) Turn the coil to the vertical position, break the field circuit and note the galvanometer deflection; make the field and again note the deflection. Why are the deflections opposite?

(d) Reverse the polarity of the fields and repeat (c), noting results.

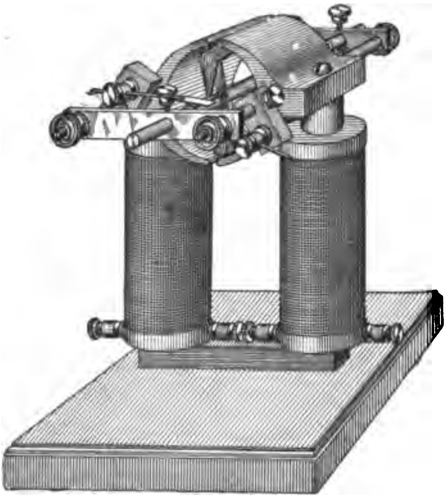


Fig. 309.—Student's Experimental Dynamo and Motor.

(e) Turn the coil so that it is horizontal; make and break the circuit as in (c). The galvanometer needle is not appreciably deflected. Why is this so, since it was stated that this was the maximum position of induction of a loop rotated in a bipolar field? Why is it different in each case?

321. Graphic Representation of an Alternating Current.—The changes in direction and magnitude of an alternating current are usually represented diagramatically. For example, suppose an alternating current of 5 amperes to flow for one second in a positive direction, and then be automatically reversed and flow for one second in the opposite or negative direction, and reversed again, this *cycle* of events continuing at regular intervals while the current flows. The action is represented in Fig. 310, where the horizontal line, P K, is divided into equal distances, PC, CF, FK, etc., representing intervals of time. The vertical line, AM, at right angles to it is divided into distances representing units of current, the current being in a positive direction when indicated above PK, and negative, when below PK. When the

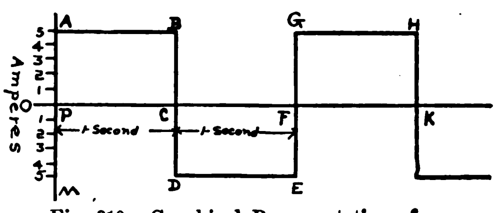


Fig. 310.—Graphical Representation of an Alternating Current.

switch is closed the current immediately rises to its full strength of 5 amperes, or from P to A, and 5 amperes are maintained constant in a positive direction for one second, A to B. When point B is reached at the end of the first second the current falls abruptly to zero, B to C, and rises to 5 amperes in a negative direction, and is maintained for an equal interval of time, D to E, when it again falls to zero, at F, and repeats the same cycle of events in equal intervals of time. The line PABCDEFGHK is called the *current wave.*

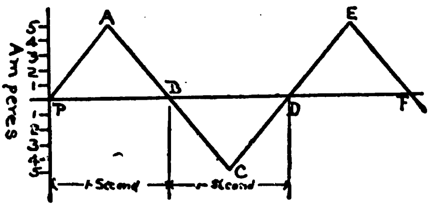


Fig. 311.—Graphical Representation of an Alternating Current.

In Fig. 310 the current is depicted as being of constant strength during each second, while it was shown in ¶¶ 291 and 320 that during rotation of the loop the current and E. M. F. varied. This variation in magnitude is represented in Fig. 311, which is constructed similar to Fig. 310, but the current gradually rises to its maximum value of 5 amperes, P to A, and as gradually diminishes again to zero, A to B, during the first second, which may also represent one-half revolution of the loop. Corresponding with the second half revolution, the current gradually rises from B, reaching its maximum negative value at C (three-quarter revolution), and falling again to zero at D, and so on. In an alternating current dynamo the alternating current wave is not so abrupt as that depicted in Fig. 311, but more truly represented by the undulatory curve, Fig. 312, which represents the same variations as before. Thus at the end of one-half second the current reaches its maximum value, 5 amperes, represented to scale by the line AG, while the value of the current at one-quarter second is equal to the line LK, or about 3 amperes.

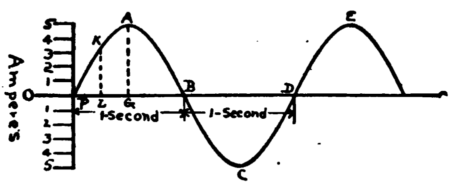


Fig. 312.—Graphical Representation of an Alternating Current.

322. Magneto Alternator.—The E. M. F. of a dynamo depends upon,

(a) *The number of lines of force cut by the armature wires,*
(b) *The number of cutting wires,*
(c) *The speed at which the lines of force are cut.*

The E. M. F. of the single loop armature, Fig. 308, will therefore be increased by winding it upon an iron core called the *armature core*, as in Fig. 313, which greatly increases the number of lines of force between the poles **N** and **S**, and also by winding a great many turns in the same direction around this core. Fig. 313 illustrates a Siemens *shuttle armature*, which is revolved between the poles of the permanent magnets, NS, and called a *magneto generator*, because the field is produced by permanent magnets. Only one turn is illustrated, but the shuttle is filled with wire, as in the cross-sectional view. This construction is only employed in small machines, Fig. 318, such as those used for magneto telephone call systems, and magnetos used in testing insulation of lines, ¶ 256. In dynamos for generating large currents, a stronger field must be employed and the armature core laminated to prevent excessive loss of energy by eddy currents, etc.

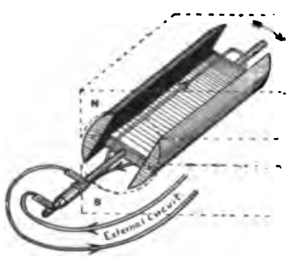
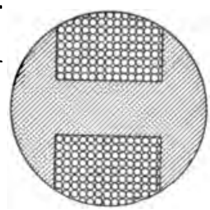


Fig. 313.—Siemens Shuttle Armature.



Cross-section of Shuttle Armature.

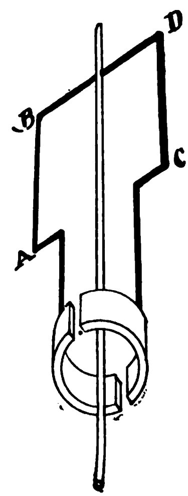


Fig. 314.—Single Armature Coil with Two-part Commutator.

323. Simple Direct Current Dynamo.—When it is desired to have the current from a generator flow always in one direction in the external circuit, like a battery current, for such purposes as charging accumulators, electroplating, etc.,

a *commutator* must be substituted for the collector rings in the simple alternator of Fig. 308. The function of a commutator is to *reverse* or *commute* the alternating current of a dynamo at the proper instant in each revolution before it flows through the external circuit. A two-part commutator, connected to the single loop, is shown in Fig. 314. It is practically a split ring, mounted upon a hub *insulated* from the *shaft*, with the parts of the ring also *insulated from each other*, as shown in the section, Fig. 315. Brushes rest upon the split ring at diametrically opposite points. The connections of a simple direct current dynamo are illustrated in Figs. 316 and 317, from which the act of commutation can be studied. In Fig. 316 the wire AB is rotated down past the **S**-pole. The direction of current is from B to A, by Fleming's rule, and to the external circuit by brush M, which is *positive;* then from the lamps to the negative brush and around the loop, CDBA. When the loop is rotated one-half revolution, Fig. 317, AB is now moving up past the **N**-pole and the direction of current in it is *reversed.* Its terminal, however, is not *now* in contact with *brush M, as before, but connected to brush P.* Current flows to the external circuit from the brush M, which is *still positive,* though the current in the armature has been reversed, as in an alternator. Brush M is consequently *always positive* and brush P always negative, or the current in the *external circuit* is a *direct current* flowing in one direction only.

Fig. 315.—Section of Two-Part Commutator.

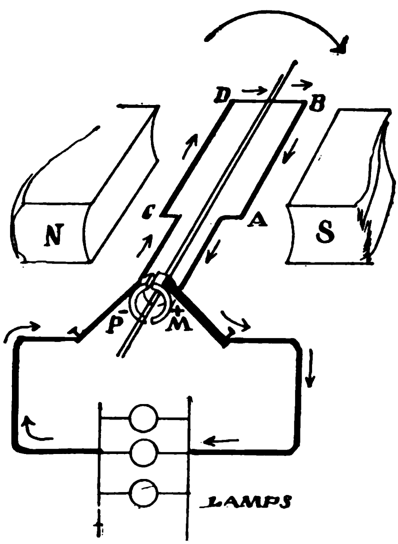


Fig. 316.—Simple Direct Current Dynamo.
At the instant depicted in the revolution brush M is positive.

The act of commutation occurs at the instant when the wire, moving down past the **S**-pole, commences to move up past the **N**-pole, either terminal of the coil being connected with one brush for one-half revolution and with the other brush for the other half of the revolution. With a two-part commutator, the current in the external circuit is interrupted twice in each revolution. A single coil armature of this type is shown in Fig. 319, where the armature core is omitted. The direction of the current is indicated by the arrows in Fig. 320, when the coil is rotated clockwise, as viewed from the commutator end.

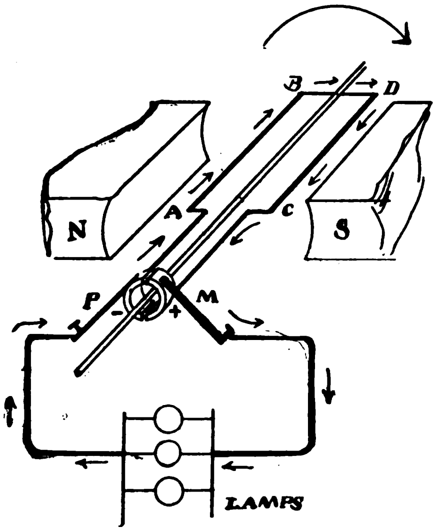


Fig. 317.—Simple Direct Current Dynamo.
Direction of current in the coil at one-half revolution from the position in Fig. 316. Brush M is positive as before.

Exp. 92: Make the same connections for the student's experimental dynamo as given in Exp. 91, page 339. Adjust the brushes so that they bear lightly upon diametrically opposite points of the *two-part commutator.*

(a) Upon revolving the shaft slowly the needle is now deflected to one side of the zero mark.

(b) Reverse the direction of rotation, and the direction of deflection (or polarity of the brushes) is now reversed.

(c) Increase the speed and the deflection increases. Why?

(d) Increase the field strength by grouping the magnet coils in parallel, so that the poles will be **N** and **S**, and the deflection is greater when the speed is the same as before. Why?

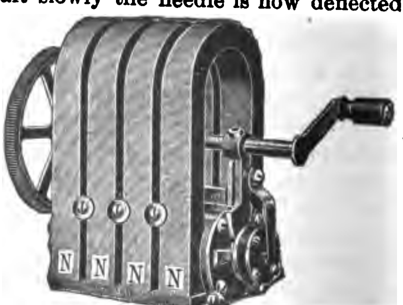


Fig. 318.—Magneto Dynamo.

Exp. 93: (a) Repeat Exp. 78, page 297, to determine the direction the galvanometer needle deflects for a given direction of current.

(b) Test with a compass and mark the polarity of the pole pieces.

(c) Determine, with the aid of the galvanometer, the positive brush for a particular direction of rotation.

(d) Apply Fleming's rule, ¶ 278, and note whether the polarity determined by this method agrees with that already determined.

(e) Reverse the polarity of the fields and again prove Fleming's rule.

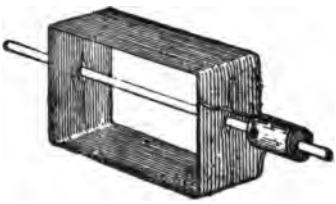


Fig. 319.—Single Coil Armature With Many Turns.

324. Graphic Representation of a Direct Current.—The same method is applicable for illustrating the direction and magnitude of a direct current as given in ¶ 321 for an alternating current. Since there is no reversal of current in the external circuit, the curve will lie above the time line, Fig. 321, and represent the magnitude of E. M. F. or current at each instant during the rotation of the loop in the two-pole field. The curve indicates a pulsating current flowing always in one direction.

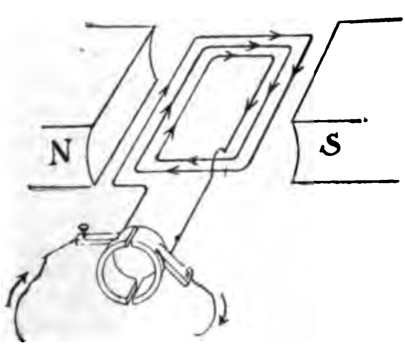


Fig. 320.—The Induced E. M. F. of Each Turn is in Series With Every Other Turn.

325. Multi-Coil Armatures.—With an armature wound with a single coil of wire the current in the external circuit is very pulsating as the coil passes through the various phases of induction represented by the curve in Fig. 321. In Fig. 306, consider two coils to be placed at right angles to each other, when, at the instant shown, the current in the vertical coil will be zero, while that in the horizontal coil will be a maximum. As rotation is continued the current in the one coil, ABCD, increases as that in the other, abcd, decreases until, at quarter revolution, current in coil A is maximum and in coil a, zero, and so on. There will thus always

be current flowing in one of the two coils, so that if they are properly joined to an external circuit the current will be less pulsating than when a single coil is used. This is depicted in the current curve of Fig. 322, where the solid undulatory line represents the pulsating character of the current produced by the two coils acting together in the same circuit. The current is thus never zero in the line as in the curve in Fig. 321. The armatures of dynamos are wound with many coils of wire, so that the current may be continuous in the external circuit.

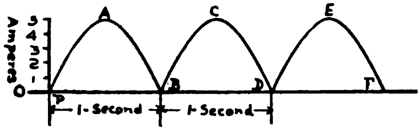


Fig. 321.—Graphical Representation of a Direct Current.

326. Gramme Ring Armature.—A four-coil direct current *Gramme* ring armature is illustrated in Fig. 323. The ring is made of a number of laminated sheets of soft iron and the coils wound upon it. The ending of each coil is joined to the beginning of the adjacent coil, so that the winding forms a complete closed circuit, or the coils are all in series. At the junction of each coil with its neighbor a lead wire is run to a commutator section, so that instead of the former two-part commutator one with four sections is now used. As the number of coils is increased the commutator sections are increased, as will be noted in the armatures depicted in Figs. 324, 325, and 329. An eight-coil ring armature is depicted in Fig. 324, rotating against the hands of a clock in a bipolar field. The connections are the same as those given above. The direction of current in the two halves of the ring is indicated by arrows and is found by Fleming's rule.

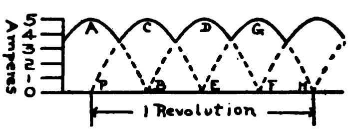


Fig. 322.—Graphical Representation of a Direct Current.

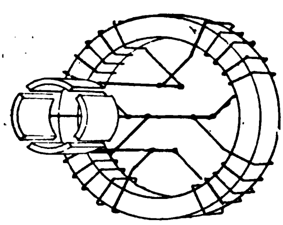


Fig. 323.—Four-Coil Gramme Ring Direct Current Armature.

When the external circuit is closed the induced current flows in both halves of the winding toward the upper or positive brush, and returns from the external circuit to the

lower or negative brush, circulating up again through each half of the armature. The windings in the halves of the armature are in parallel with the brushes. As each coil passes from under the influence of the **N**-pole and comes into action under the **S**-pole, commutation takes place and the direction of current through it is reversed, as will be seen from tracing the direction of the currents in the two upper coils, which are opposed to each other. The brush is located at this point of opposition and serves to conduct the current from both halves of the ring to the external circuit. The brushes resting upon two adjacent bars will thus short-circuit each coil for an instant as it passes from pole to pole, and this short-circuiting should occur when there is zero E. M. F. in the coil, or at that instant when the magnetic lines threading through it are a maximum, which will be when its plane is at right angles to the lines of force threading through the iron ring. The act of commutation is further described in ¶ 338 and Fig. 351.

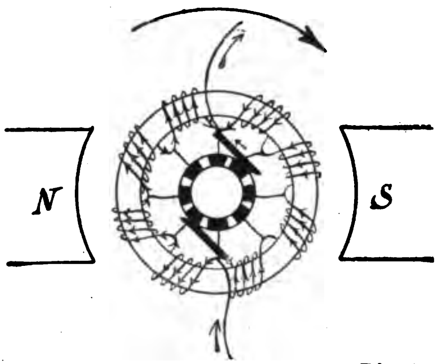


Fig. 324.—Eight-Coil Gramme Ring Direct Current Armature.

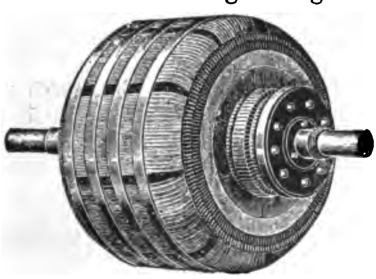


Fig. 325.—Multi-Coil Gramme Ring Direct Current Armature.
Smooth core pattern.

327. Induced E. M. F. in a Ring Armature.—The upper and lower coils in the right-hand half of the ring armature, Fig. 324, will have about the same E. M. F. induced in them, say 2 volts each, while the two coils between them will have a higher E. M. F. at the same instant, say 4 volts each, since they occupy nearly the position of the maximum rate of change of the lines threading through them. The total E. M. F.

of this half of the ring, since these *four coils* are in *series* will therefore be 2 + 4 + 4 + 2 or 12 volts, and since similar induction takes place in the other half of the ring at the same instant, there will be a total of 12 volts induced in it. The windings of the *two halves being in parallel*, the E. M. F. at the brushes will also be 12 volts, just as though each half represented a cell of 12 volts E. M. F. and the two cells were placed in parallel. The current in the external circuit will be the sum of the currents in each half of the windings. If it is 10 amperes, 5 amperes will flow through each half of the ring. The adding together of the E. M. F.'s in the coils, and the current flowing from them, may be understood from the following battery analogy. In Fig. 326, eight cells represent the above armature coils and are connected 4 in series and 2 groups in parallel. The E. M. F. across the lead wires is 12 volts, and with 10 amperes in the external circuit 5 amperes flow through each group of cells. The E. M. F. of one group of cells is the sum of the E. M. F.'s of the cells connected in series in that group, or 2 + 4 + 4 + 2 = 12 volts, and the E. M. F. of 2 groups in parallel is 12 volts. If 10 amperes flow through the external circuit, 5 amperes will flow through each group of cells.

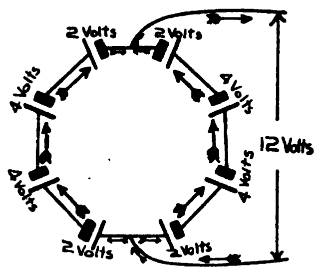


Fig. 326.—Battery Analogy of Induced E. M. F. in a Ring Armature.

By employing 8 coils on this ring armature the current is less pulsating than in the four-coil armature, Fig. 323, and is represented by the wave in Fig. 327. As the armature coils are further increased, the wave becomes more nearly a straight line, but there will always be a slight pulsation of the current.

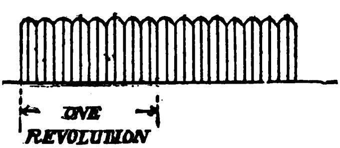


Fig. 327.—Direct Current Wave of a Multi-Coil Armature.

Prob. 118: The joint resistance of the two halves of an 8-pole ring armature is .5 ohm. This is called the *armature resistance* and would be measured between the brushes. What is the resistance of the wire upon the armature?

By Formula (45) $R = J. R. \times nq = .5 \times 2 = 1$ ohm.
J. R. $= 0.5$ ohm, $nq = 2$ halves in parallel.

R = resistance of one-half the armature, therefore the total resistance of the wire upon it $= 1 \times 2 = 2$ ohms.

The resistance of the armature winding is thus four times the joint resistance from brush to brush in this type of armature.

Prob. 119: The resistance of the eight coils, in series, upon the ring armature, Fig. 324, is 4 ohms, what is the *armature resistance* from brush to brush?

The resistance of one-half of the armature is $4 \div 2 = 2$ ohms. The joint resistance of the two halves in parallel is,

$$\text{By Formula (43)} \quad \frac{2}{2} = 1 \text{ ohm.}$$

The resistance of the wire upon this ring armature is therefore *four* times its joint resistance.

Prob. 120: The E. M. F. generated by the ring armature in Fig. 324 is 12 volts, the armature resistance 1 ohm, an incandescent lamp connected to the brushes 2 ohms, leads to lamp 1 ohm. What current will the lamp receive? See Fig. 328.

$$\text{By Formula (31)} \quad I = \frac{E}{R + r} = \frac{12}{2 + 1 + 1} = 3 \text{ amperes.}$$

$R = 2 + 1 = 3$ ohms, $E = 12$ volts, $r = 1$ ohm.

Prob. 121: What potential will a voltmeter indicate when placed across the brushes in Prob. 120? See Fig. 328.

By Formula (29) $E = I \times R = 3 \times (2 + 1) = 9$ volts.
$I = 3$ amperes, $R = 2 + 1 = 3$ ohms.

The pressure required to send 3 amperes through the armature will be $E = I \times r = 3 \times 1 = 3$ volts, or $12 - 9 = 3$ volts.

By substituting a pair of collector rings for the commutator, the ring armature of Fig. 324 will give an *alternating current* to the external circuit. The winding is the same but only two lead wires are taken from the coils, at points diametrically opposite and connected one to each collector ring. With the increased number of coils the alternating E. M. F. is increased, since the E. M. F.'s in the coils at any instant are in unison. The commutator and collector rings may both be mounted on the same armature shaft, when the machine will give either a direct or alternating current, or both, at the same time to two

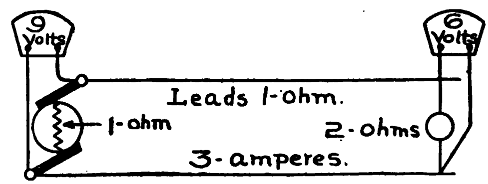


Fig. 328.—E. M. F. and P. D. of an Armature.

independent circuits. The dynamo would then be called a *double current generator.* The collector rings would be connected one to each diametrically opposite section of the commutator; for example, 1 and 5 in Fig. 324.

328. Siemens Drum Armature.—Instead of winding the armature coils upon a laminated ring, they are sometimes

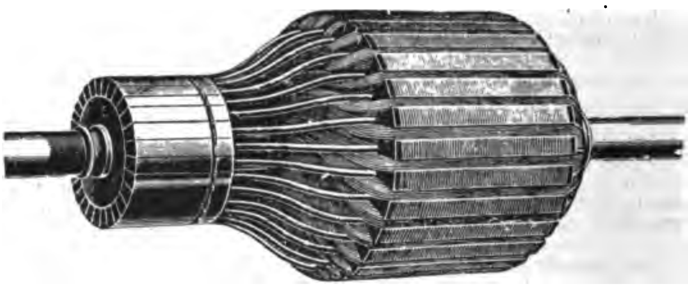


Fig. 329.—Multi-Coil Siemens Drum Armature. Tooth-core pattern.

wound upon a cylindrical laminated iron core made by assembling, upon the armature shaft, thin sheets of soft iron; after being properly insulated the coils are wound upon the core, and connected in series and to the commutator in the same manner as that given for the ring armature. Fig. 330 depicts a four-coil Siemens drum armature with its commutator, suitable for a bipolar field. In practice a great many coils are wound upon the core covering its entire area, the commutator sections increasing with the subdivision of the armature coils. The induced E. M. F. in that part of a coil under one pole is in the opposite direction to that in the other half of the coil so that the two E. M. F.'s are in series, as in two consecutive coils in the ring armature. Both halves of the drum armature coils are in parallel with the external circuit so that

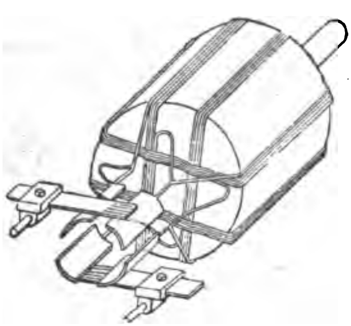


Fig. 330.—Four-Coil Siemens Drum Armature.

the induced E. M. F. is that generated by one-half of the total conductors upon the core, and each half of the windings deliver one-half of the total current flowing to the external circuit.

329. Advantages of Drum and Ring Armatures.—The difference between the ring and drum armature is that in the former, the *active wire* of each coil cutting the magnetic lines

Fig. 331.—Tooth-Core Armature Body With Two Formed Coils in Position

The wound and formed coils are also illustrated. The armature is intended for a six-pole field.

of force is that part located only on the periphery of the ring while that on the ends and inside of the ring cuts no lines of force, and is termed *dead wire.*

This serves only to conduct currents from one active conductor to the next. In the drum type there is less dead wire, since each half of the coil cuts magnetic lines of force, and that on the ends of the core is only inactive and serves

to connect the active conductors. The I^2R loss in a ring winding will thus be greater than in a drum armature of the same capacity. On the other hand, in ring armatures the coils can be much better insulated from each other, and are more readily accessible for repairs than in the drum armature. For these reasons high voltage direct current arc lighting dynamos are generally constructed with ring armatures. A combination of the drum and ring winding in what are known as *drum-wound ring armatures* is extensively used in practice and further described in ¶ 330.

330. Drum-Wound Ring Armatures.—Some of the advantages of both the drum and ring windings are obtained by using a *slotted laminated ring* armature core and winding the wire, drum fashion, upon this ring, Fig. 331.

There are thus two active conductors for each coil, as in the drum type, and the width of the coils is such that when one of these conductors is passing under a **N**-pole the other passes under a **S**-pole. The direction of a current will thus be opposite in each half of the coil underneath the poles, and so flow around the coil in the same direction. Fig. 331 depicts an armature having a slotted *tooth core* built up from punchings of thin sheet iron and held in position by two flanged iron rings securely fastened to the spider arms, as shown. The coils are first wound, then properly shaped upon formers, removed, wrapped with insulation, varnished and baked, and then placed in the slots of the armature core. The winding is held down by clamps at each end and the coil terminals properly connected to the commutator. The coils shown are intended for a six-pole field, which is practically three bipolar fields, and constitute a *multipolar field*, ¶ 346. In some types of large size dynamos, solid copper bars, properly insulated, varnished, baked, etc., are placed in the armature slots, which are lined with mica formed tubes. The bars are then connected by flexible formed terminals, according to the method of winding.

331. Open-Coil Armatures.—The armatures previously described are called *closed coil armatures*, because the coils are all connected, forming a closed winding around the armature. When very high potentials are to be generated, as, for example, 8000 volts for a series constant current arc-lighting circuit, ¶ 348, the closed coil winding is not as suitable, since the potential difference between adjacent commutator bars

becomes very high, and may jump or "flash" from bar to bar, or even from brush to brush. Open coil armatures are designed to obviate this difficulty, and are used principally for arc lighting.* A simple form of open coil armature is depicted in Fig. 332. Two coils, A,B, wound at opposite positions on the ring core are connected in series, and the two remaining terminals to two diametrically opposite commutator bars, 1,2. Another set of two coils, C,D, are wound in a position at right angles to the former coils, connected two in series, and to two independent diametrically opposite bars, 3 and 4. At a particular instant of revolution, shown in Fig. 332, the coils C and D have the maximum E. M. F. induced in them, and are connected to the external circuit by the brushes, while coils A and B are in the position of zero induction and out of circuit at this instant. An instant later coils A and B will be in the active position and connected to the circuit with coils C and D cut out. Two independent two-part commutators are used instead of that shown in Fig. 332 and placed side by side, Fig. 333, one set overlapping the other. The brush is made equal to the width of both sets of bars, and by this arrangement the external circuit is not broken each time a pair of coils is switched out of circuit. With the four-coil armature the current would be very pulsating in the external circuit, so that more coils are used in practice and more commutator segments, or several commutators similar to Fig. 333, placed side by side on a shaft, and their respective brushes connected in series or parallel with the external circuit, so as to obtain the maximum inductive effect of all the active coils. For example, the open-coil armature of a 160-light Brush arc generator is wound with 32 bobbins, and at one instant of revolution there

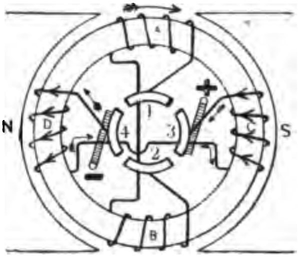


Fig. 332.—Open-Coil Armature.

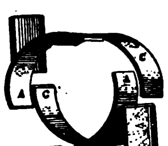


Fig. 333.—Commutator for an Open-Coil Armature.

*In Brush and Thomson-Houston direct current arc-light generators and in Westinghouse alternating current arc generators. The Wood, Excelsior, and Western Electric dynamos are closed coil ring armatures, subdivided into a great many sections to reduce the potential between adjacent commutator bars.

are 2 sets of 4 coils each in series; 2 sets of 4 coils each in series, with 2 groups in parallel, and 2 sets of 4 bobbins each out of circuit. The E. M. F. generated by this armature is 8000 volts.

QUESTIONS.

1. How does a dynamo differ from a primary battery?

2. Give three classifications of dynamos according to their mechanical construction.

3. How does an alternator differ from a direct current dynamo?

4. Sketch four positions of a single rectangular coil of wire at each quarter of a revolution when rotated in a bipolar field, the terminals of the coil being provided with two collector rings. Indicate polarities and direction of current in the internal and external circuits in each sketch.

5. Make sketches when the terminals of the coil in question 4 are connected to a two-part commutator.

6. The armature of a dynamo revolving at 1000 revolutions generates 110 volts. State three ways in which you can increase the voltage.

7. What is the difference between a drum, a ring, and a drum-wound ring armature? State the advantages of each.

8. What is the advantage of open-coil armatures over the closed-coil type?

9. Make sketch of a 12-coil direct current bipolar ring armature with two turns per coil; indicate direction of current in the armature and external circuit.

10. The resistance of the wire wound upon a bipolar ring armature is 20 ohms. What is the armature resistance? *Ans.* 5 ohms.

11. The armature in question 10 generates an E. M. F. of 50 volts. What current will flow through some lamps joined in parallel with it having a joint resistance of 4 ohms; resistance of lead wires 1 ohm? *Ans.* 5 amperes.

12. What will be the P. D. indicated by a voltmeter, in question 11, when placed (1) Across the lamps? (2) Across the brushes? *Ans.* (1) 20 volts; (2) 25 volts.

LESSON XXVII.

ARMATURES.

Armature Core Construction—The Commutator and Brushes—Armature Core Insulation—Table XXI. Insulation Test—Armature Winding—Armature Core Loss-Hysteresis—Armature Reactions—The Act of Commutation of an Armature Coil-Sparking at the Brushes—Position of the Brushes—Causes of Sparking—Capacity of a Dynamo—Commercial Rating of Dynamos—Losses in a Dynamo—Efficiency of a Dynamo—Questions.

332. Armature Core Construction—*Eddy Current Loss.*—The armature core which is introduced into the magnetic circuit to lower its reluctance, is an electrical conductor also, and when rotated in the magnetic field will have currents induced in it, according to the principles of electromagnetic induction. A certain portion of the energy driving the armature is thus expended in producing useless electric currents, *eddy currents*, ¶ 292, in the core, and which do not appear in the external circuit; this is termed *eddy current loss*, and constitutes one of the internal losses of a dynamo.

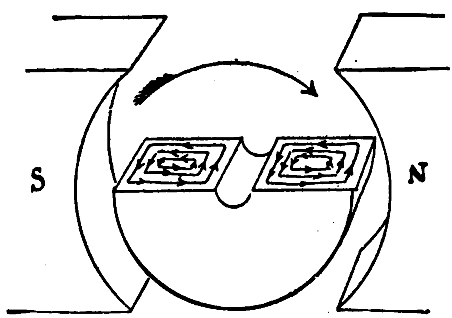


Fig. 334.—Eddy Currents in the Armature Core.

A section of a solid armature core is illustrated in Fig. 334, and the direction of the induced eddy currents (found by Fleming's Rule, ¶ 278), indicated at this particular position of the armature core in the course of its revolution. The heat produced by these currents is chiefly at the outer surface of the core, where the eddies are strongest. The armature wires being wound on the surface will also be heated and their resistance in-

creased, and as a result the I^2R loss will be increased. There are thus two evil effects of the eddy currents.

Eddy current losses may be considerably diminished by building the armature up of a series of thin discs of soft sheet iron or steel, the surfaces of which have been allowed to oxidize (rust), thus introducing an insulator between the sheets, which decreases the electrical conducting power of the core. Sometimes pieces of tissue paper are interposed between the sheets, or brass discs introduced at intervals to break the continuity of the circuit, and also to afford armature ventilation. A single sheet iron punching of a tooth-core ring armature is represented in Fig. 335, while the effect of lamination is shown in Fig. 336, in which the eddies are confined to each lamination. Only four laminations are purposely shown in the core, in Fig. 336, to magnify the effect. The thickness of the metal from which they are punched may be .015 inch, so that a great many separate pieces are required for a single armature core.

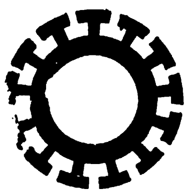


Fig. 335.—Sheet Iron Armature Core Disc. .015-inch thick.

333. The Commutator and Brushes.—A commutator consists of a number of bars or segments of drop-forged, hard drawn copper, assembled around an iron hub and thoroughly insulated from the hub and from each other, Fig. 337; mica is used for the insulation. The bars must be securely held in place, since a high or low bar would cause a break in the circuit each time it passed under the brush and destructive arcing would result. A simple method of construction is illustrated in Figs. 338, 339, etc. A brass or iron hub of the shape shown in the sectional view, Fig. 338, drilled to receive the armature shaft, is insulated with a sleeve

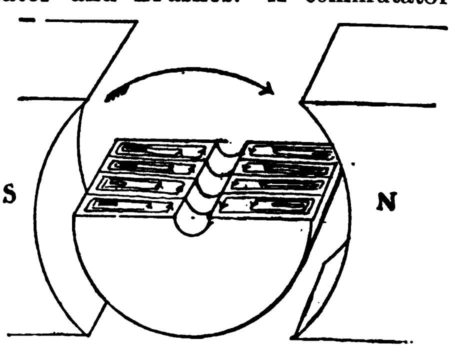


Fig. 336.—Laminated Armature Core. The thickness of the discs is magnified to show the eddy currents.

and formed collar made of sheet mica, when it is ready for the reception of the bars which are forged with grooves in the ends, as in Fig. 339. The projecting insulated tongue on the hub fits into a corresponding groove in a bar, and when all the bars are assembled around the hub, with strips of mica between each, they are locked in place by the projecting insulated **V**-tongue of a washer screwed upon the hub and backed up by a lock-nut. A partial section through the commutator is shown in Fig. 340, in which the heavy line represents the insulation, and from which the manner of locking the bars will be understood. A lug extends at right angles from one end of each bar to which the armature wire is soldered. Carbon brushes, copper plated to decrease their resistance, are secured in a brush holder and made to press against the commutator by spring pressure. Details of the brush holder are shown in Figs. 304 and 361. The brush holder stud or shaft is securely bolted to, but insulated from, the rocker arm, and connected by flexible cables to the external circuit. The function of the rocker arm is to move the position of the brushes upon the commutator so that the current is led away from the armature at the proper point of commutation. Fixed copper brushes are used upon alternators because there is no tendency to spark at the brushes, as in direct current machines, and copper is a much better conductor. In very low voltage dynamos copper brushes are used to advantage.

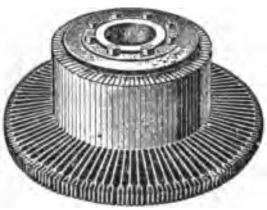


Fig. 337.—Commutator for a Direct Current Dynamo or Motor.

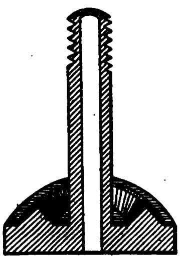


Fig. 338.—Commutator Hub. Made of brass or iron.

334. Armature Core Insulation.—The armature cores of all large generators are slotted for the reception of the conductors and are called tooth-core armatures, Fig. 341. Mica tubes, formed by the aid of heat, from sheets built up of many thicknesses of mica united by shellac, etc., are fitted into the

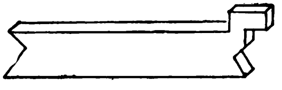


Fig. 339.—Forged Copper Commutator Bar.

slots and formed rings or segments of the same material are used upon the ends of the cores. The quality of the insulation and the care required in insulating increases directly with the potential to be developed by the armature; an armature wound to develop 1000 volts requiring a better degree of insulation than one wound for only 125 volts. Smooth core armature bodies are used in some small machines and are generally wound with several layers of linen or silk, then shellaced and baked in an oven to drive out all moisture. The armature discs are bolted between end flanges, the circumference of which are slotted for the reception of small fibre wedges, which serve as guides for the coils to be wound upon the core, Fig. 342. The insulation is pierced and the wedges driven into the slots.

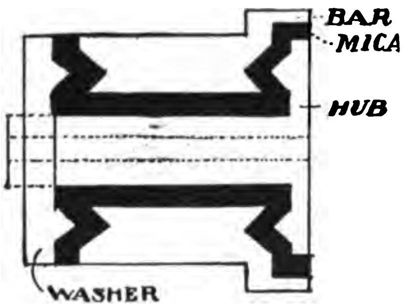


Fig. 340.—Sectional View of a Commutator.

Fig. 341.—Tooth-Core Armature Body With Formed Coils in Position.

The quality of an insulating material is tested by subjecting it to a high potential and ascertaining at what voltage the insulation "breaks down," or conducts, instead of insulates. The specimen to be tested, as a piece of paper or fibre, may be interposed between two plates connected to a source of high

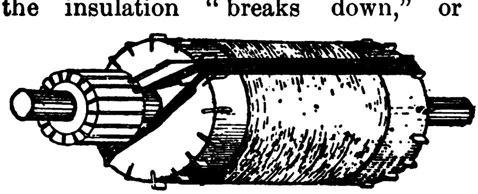


Fig. 342.—Drum Armature Showing the Method of Winding a Coil.

potential, which is capable of being regulated. The voltage is then increased till a spark passes from plate to plate through the specimen, thereby puncturing it, as in Exp. 88, page 323. The following insulating materials and the voltages at which they "broke down" under test will give the student some idea of what is meant by insulating qualities.

Table XXI.—Insulation Test.

"Break Down" Voltage	Thickness in Inches	Material
2000	.013	ordinary shipping tag
500	.010	soft grey wrapping paper
800	.015	varnished linen
800	.016	white gummed tape
1500	.031	varnished canvas
2000	.037	red sheet fibre
5000	.022	yellow press-board
6500	.018	mica and cheese cloth
8500	.035	grey press-board

The insulation of electrical machinery is usually tested by applying several times the voltage that the apparatus is designed to stand; for example, a 1000 volt armature may be subjected to 10,000 volts, one terminal of the high potential source being connected to the core, and the other to the copper windings. If there is any defect in the insulation, upon application of the high voltage it will readily be noted on indicating instruments in the testing circuit.

335. Armature Winding.—After complete insulation of the armature core it is ready to receive the armature wires. In large tooth-core bodies the conductors are generally in the form of straight bars of rectangular cross-section which have been previously insulated. One or more bars are inserted in each slot, and the coils formed by connecting their ends to other bars by flexible formed end terminals soldered to them, provision being made for commutator taps at the ends of the proper coils, when the armature is for a direct current machine. There are many kinds of armature connections, each designed for a specific purpose, such as series winding, double or triple multiple-winding, multiple-wound two-circuit winding, etc.* A small smooth-core drum armature body for a two-pole field is depicted in Figs. 342 and 343. Suppose it

* Armature winding is treated in books relating to dynamo design.

is to be wound as a closed coil series wound armature with 8 coils and 3 turns per coil. The armature core is divided into 16 divisions by the fibre wedges alluded to in ¶ 334, and the first coil wound in division 1 and 9; the second, in 2 and 10, and so on. Commence to wind the beginning of coil No. 1 in division 1, and it will end in division 9, Fig. 343; commence coil No. 2 in division 2, wind in the same direction as coil No. 1, and it will end in division 10, and so on. The coils should then be bound to the armature core by mounting it in the lathe and winding several bands around them, each consisting of a number of turns of phosphor bronze wire. Mica is interposed between the band wires and the armature wires, and the former soldered together, thus producing a solid band. A commutator with 8 bars will be required since there are 8 coils and the coils are to be joined in series. Connect the beginning of coil No. 1 to bar 1 and the ending of coil No. 1 to bar 2, Fig. 344; the beginning of coil No. 2 to the ending of coil No. 1 at bar 2; the ending of coil No. 2 to bar 3 and to the beginning of coil No. 3, and so on until finally the ending of coil 8 will connect to the beginning of coil 1 at bar 1. The coils are thus all in series around the armature; the commutator bars forming the connecting links between the coils. Many more turns could be wound per layer, and more layers per division, to increase the induced E. M. F. After the first set of coils is wound a second set may be wound on top of them, with

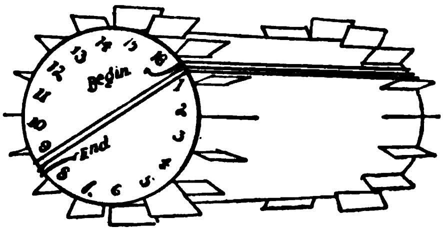


Fig. 343.—Position of the Coils on a Drum Armature.

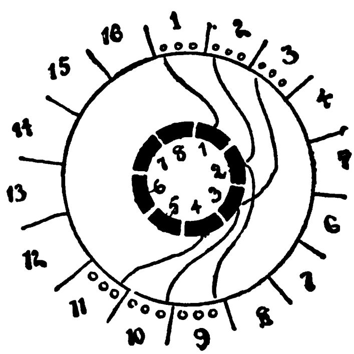


Fig. 344.—Connecting the Armature Coils to the Commutator.

proper insulation between them; 16 bars would have been required had this method been adopted in Fig. 343. The method of varying the winding according to the potential desired is illustrated in Fig. 345, which represents the number of wires per coil on an 8 H. P. dynamo when it is wound for 125 volts, as in A; 250 volts, in B; 500 volts, in C. The size of the wires decreases as the voltage increases, since for the same power the current will be less, and the turns increase in direct proportion to the voltage, there being 3, 6, and 12 turns

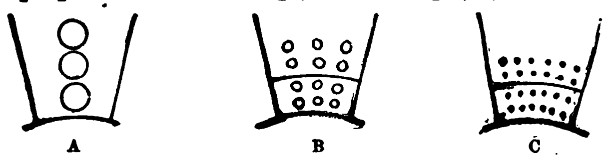


Fig. 345.—Windings of an 8 H. P. Armature.
A—125 volts. B—250 volts. C—500 volts.

per coil corresponding to 125, 150, and 500 volts. The speed and field strength are the same for each armature. In B and C two coils are shown per division, but they are connected in series as in case A. In a series closed circuit *ring winding* the same method will apply as given above. The end of the first coil is connected to the beginning of the second, and the junction, to commutator bar No. 2, and so on, until the ending of the last coil is connected to the beginning of the first coil and to bar No. 1. This method is outlined in the multipolar ring armature in Fig. 359.

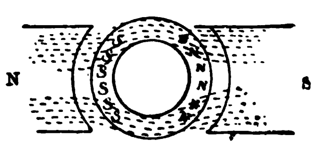


Fig. 346.—Armature Core Loss—Hysteresis.

336. Armature Core Loss—Hysteresis.—The iron core of an armature rotating in a two-pole field will be subjected to two opposite magnetic inductions in each revolution. For example, consider the polarity of the core at one instant during its revolution, Fig, 346; the left-hand side of the ring has a **S**-pole induced in it by the **N**-pole of the field magnet, while the right-hand side of the ring possesses an induced **N**-pole from the **S**-pole of the field magnet at the same instant. At one-half revolution of the ring from this point that part which previously possessed induced **N**-polarity is now inductively magnetised with a **S**-pole, and the other half, with a **N**-pole. The ring is thus

subjected to two opposite magnetisations in each revolution. Suppose the speed to be 2000 revolutions per minute, then there will be 4000 reversals of magnetisation per minute in the core. Heat is developed as a result of the hysteresis (page 308, Exp. 82). A portion of the energy required to drive the armature is thus expended in heating the core and does not appear as useful electrical work. The heat so generated also heats the copper wires wound upon the armature core, increasing their resistance and the I^2R loss, so that still more energy is wasted which does not appear as useful energy. This is called hysteresis loss in a dynamo.

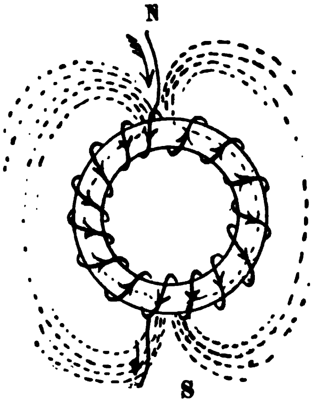


Fig. 347.—Magnetic Field Produced by Current Circulating Through the Armature.

337. Armature Reactions. The current flowing from an armature circulates through its internal windings, and produces magnetic poles in the armature core which react upon the magnetic field and distort it. Suppose current to be flowing in the direction indicated, from the armature windings depicted in Fig. 347, a **N** and a **S**-pole are produced at diametrically opposite points, where the current enters and leaves the armature by the brushes, just as in the case of the plain iron ring C, of Fig. 178. Now when this armature is placed in its field and current flows from it, Fig. 348, its poles induce two poles in each of the field cores by magnetic induction, with the polarities as indicated.

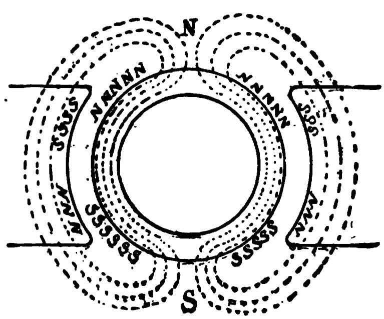


Fig. 348.—Reaction of the Armature Field Upon That of the Field Magnets.

One induced pole in each field core tends to strengthen the number of lines of force threading from the field to the armature core, while the other induced pole tends to neutralize the field magnetism or to produce neutral points in the field at the opposite ends of a diameter. This will be more clearly understood from Fig. 349, which represents the resultant distorted magnetic field produced by the cross-magnetising effect of the armature upon the field. The neutral points near two of the pole tips and the points where the lines are crowded under the other two pole tips are shown by the aid of iron filings. In the armature core, N and S represent the poles induced by the field magnets, while the poles in the core due to the armature current are represented by s and n.

Fig. 349.—Distortion of the Magnetic Field Due to the Cross-Magnetising Effect of the Armature Current.

The position of maximum induction then is not along the horizontal line, as considered in the ideal dynamo ¶ 319, but along a line inclined at an angle to it, the angle increasing as the current from the armature increases. As a result of this field distortion the position of minimum inductive action in the armature coils will not be along the vertical line A B, Fig. 350, but along a line somewhat in advance of it, in the direction of the armature rotation, as the line CD which passes through both neutral points in the field and is known as the *neutral line*, or plane.

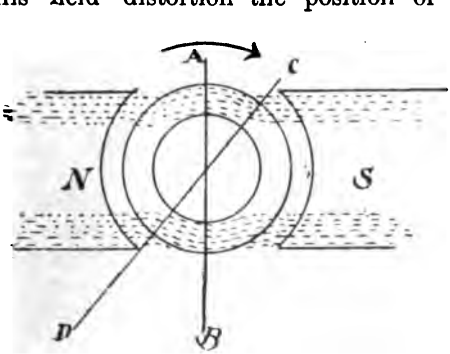


Fig. 350.—Neutral Points Produced by the Armature Reaction.

Commutation of an armature coil must therefore take place as the coil passes the neutral line. The brushes should be set at diametrically opposite points (in a bipolar dynamo) and then shifted to a position corresponding with the neutral

line. The angle of advance of the neutral line from the vertical position will depend upon the current flowing from the armature (the field distortion increasing with the current) being shifted forward for an increase, and backward for a decrease in the armature current. The brushes must therefore be shifted forward in the direction of rotation for an increase of current from the machine and backward, for a decrease. When the brushes are not set to correspond with the neutral point, sparking at the brushes will result.

338. The Act of Commutation of an Armature Coil— *Sparking at the Brushes.*—The act of commutation of an armature coil, that is, the moment it is passing from under the influence of one pole to come under that of the other, is illustrated in Fig. 351. For an instant, each coil is completely short-circuited by the toe of the brush, and any induced E. M. F. in the coil will cause a current to flow through it. As the coil moves away from the brush this circuit is broken and a bright spark appears at the point where the commutator bar leaves the brush, due to the self-induction of the coil produced by this current. Each coil is thus short-circuited as it passes underneath each brush, so that the sparking may become continuous when the dynamo is running. If the E. M. F. induced in an armature coil of .01 ohm resistance is only .1 volt at the neutral point, by Ohm's Law the current for the instant will be $\frac{E}{R} = \frac{.1}{.01} = 10$ amperes.*

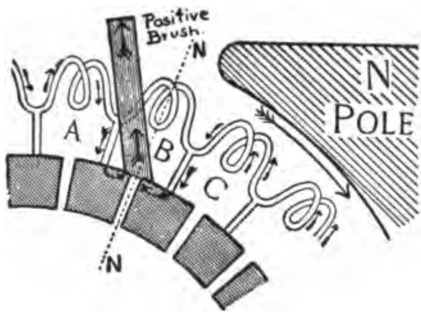


Fig. 351.—The Act of Commutation of an Armature Coil.

At the instant shown coil B is short-circuited by the brush.

If the brushes are not exactly at the neutral point, the coils are then short-circuited before they reach the neutral

*** Suppose that the brush in Fig. 351 had been made of copper instead of carbon, as is generally used, its resistance would have been less and a greater current would have circulated around the short-circuited coil, increasing the self-induction and probably melting a piece of the brush by the heat of the arc.**

point, and the E. M. F. in them is higher, causing a greater current to rise for the instant, which is noticed by an increase in sparking at the brushes. *To find the neutral, or non-sparking point of a dynamo, when it is running, the brushes are rocked backward or forward until the sparking practically disappears, or until a point is found where it becomes a minimum.* The tendency of a dynamo to spark can be entirely eliminated if, in construction, the armature is divided up into many coils. Each coil will then have only a few number of turns, which will keep the self-induction down, when the induced E. M. F. will be very small, as a small coil can more nearly occupy the neutral point. The modern dynamo has been so perfected that the sparking has been entirely eliminated. Many dynamos, however, do spark at the brushes, but the fault lies in the manner of adjusting the brushes, etc., rather than in the machine itself. Some of the causes of sparking are given in ¶ 340.

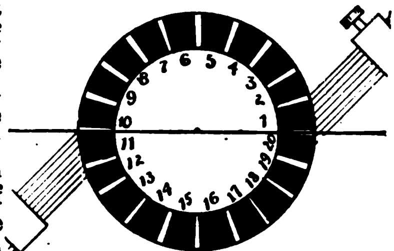


Fig. 352.—Brushes Set Diametrically Opposite on the Commutator of a Bipolar Dynamo.

Fig. 353.—Armature Winding.

339. Position of the Brushes.—The brushes must be first set on the commutator at the opposite ends of the diameter, in bipolar dynamos, or diametrically opposite. This is usually done by counting the number of bars in the commutator and then properly dividing them. Suppose that a commutator has 20 bars, the toe of the brush should then be set to the insulation line between bars 1 and 20, and between bars 10 and 11, as in Fig. 352. In multipolar dynamos there are usually as many sets of brushes as pole pieces, so that the whole number of commutator bars is

divided into four equal parts for a 4-pole machine, and so on Suppose a commutator of a 4-pole dynamo to consist of 144 segments, then the toes of the brushes would be set to the insulation line between 144 and 1; 36 and 37; 72 and 73, and 108 and 109. To facilitate the construction and manipulation of the brushes in bipolar dynamos, the armature coils are so connected that the brushes can be set at the ends of a horizontal diameter, and still be in connection with the armature coil as it is passing through the neutral point. This is accomplished by *connecting the armature on the quarter*, as it is termed. In Fig. 353 the terminals of coil 1 are not connected to the commutator bar immediately below it, but carried around to a distance of one-quarter the whole number of bars and connected to bar 3. It will thus be seen that while coil 1 is in the vertical position, its terminals are at the end of a horizontal diameter, at which point the brushes should be located. In Fig. 354 is shown the relative position of the brushes of a 2-pole dynamo; 1st, running full load; 2d, half load; 3d, no load. The brushes are therefore gradually advanced from position 3 to position 1 as the dynamo is loaded, and likewise rocked backward from 1 to 3 as the load is diminished. The shaft which holds the brushes is attached to a cradle or arm, which can be moved to properly shift the brushes; hence the name "rocker arm." In some makes of dynamos the brushes, after being rocked to the neutral point, need not be again adjusted for any change in load. The neutral point in these machines is made practically constant by designing the armature so that the armature poles will be saturated on light load. The neutral line will then be practically constant, instead of advancing with the increase in load. On account of the very

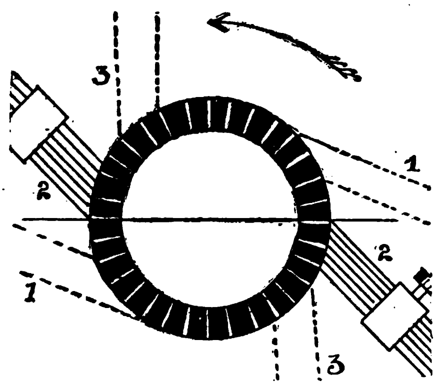


Fig. 354.—Shifting the Position of the Brushes.
3—No load. 2—Half load. 1—Full load.

high potential used in arc light dynamos a small amount of sparking at the brushes is permissible.

340. Causes of Sparking.—

1. Brushes are not set at the neutral point. They should be rocked till this position is found.

2. Brushes are not properly spaced with reference to the commutator bars. They should be accurately and equally spaced by counting the bars between them.

3. Brushes are not set with sufficient pressure against the commutator.

4. Brushes are not set to obtain the full area of contact with the commutator.

5. A high, low, or loose commutator bar causing poor contact with the brush.

6. Loose connection between armature coil and commutator bar. This will be noted by a peculiar blue snapping spark just as this particular bar passes under the brush.

7. Commutator is worn in ridges, causing an uneven surface for brush contact.

8. Armature section is short-circuited by a breakdown in the insulation, either in the coil or between commutator bars, causing a heating of the armature. If the machine can be stopped for a short time this coil should be disconnected, its ends taped, and a wire of the same size as that used in the armature used as a bridge to connect the commutator bars formerly connected to the detached coil. The continuity of the armature circuit will thus be maintained and the machine can be run till the coil can be rewound.

9. Overload on the dynamo. This will be noted by the ammeter in the circuit, also by the sparking of the brushes and the increased temperature rise of the machine.

10. Collection of dirt and grease on the commutator, which assists in preventing a good brush contact.

11. Commutator bars are short-circuited by a collection of carbon or copper dust around them. The commutator should be kept clean, and generally requires no lubricant when carbon brushes are used.

341. Capacity of a Dynamo.—With sufficient power applied to a dynamo it is possible to greatly increase the current which can be taken from it, but a limit is soon reached in one or more of three ways.*

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* The student should read again ¶ 282 upon Lenz's Law for induced currents.

First. By an excessive drop in the machine, due to an overload, which decreases the P. D at the brushes, when the lamps connected thereto will then receive insufficient current and burn dimly. The E. M. F. can be increased by increasing the speed, but from a mechanical standpoint there is a limit to the speed of rotation which cannot be exceeded, so that some of the load must be removed from the external circuit when this condition is attained.

Second. By an excessive heating of the dynamo. As previously stated the heat from the armature increases four-fold when the current from it is doubled, ¶ 259. A machine might be operated with its copper conductors slightly below red-heat, but since this would destroy the insulation of the wires, internal closed circuits would then be formed, and the energy would not be conducted to the external circuit. It is not desirable to work a machine above the boiling point of water (212° F.) and generally the permissible rise is about 70° above the surrounding air. In a hot engine room at a temperature of 100° F. then, the machine would be run at 170° F. The temperature of a generator is determined by running it from 6 to 10 hours at full load, stopping it, and then placing thermometers against the hottest parts for a short time, as a half-hour, a piece of cotton-waste or other non-conductor of heat being laid over the thermometer.

Third. By excessive sparking at the brushes of the generator. This subject is treated in ¶ 338.

342. Commercial Rating of Dynamos.—Dynamos are rated in size, according to the number of kilowatts which they are capable of maintaining in the circuit external to their terminals within the limit of permissible heating. For example, a 60-K. W. 100-volt generator means that the machine will deliver 60 K. W. to the circuit external to its terminals,* and that 100 volts P. D. will be maintained at this output across the terminals. The current, therefore, at full load will be, by Formula (63) $60000 \div 100 = 600$ amperes.

Owing to the electrical losses in the armature and fields the total K.W. generated is higher than the machine's rat-

*The potential difference at the brushes and the terminals of shunt dynamos is practically the same, but in a series or compound wound dynamo the potential at the brushes is higher than that at the terminals, on account of the $I \times R$ drop in the series field, ¶¶ 351 and 353. The student should keep this point in mind when solving problems.

ing. For example, the 60-kilowatt machine alluded to may develop 62.5 K.W., of which only 60 K.W. can be utilized in the external circuit. Compare with the power from cells, ¶ 226.

343. Losses in a Dynamo.—There are two classes of losses in a dynamo,

(*1.*) *Mechanical losses,*
(*2.*) *Electrical losses.*

(1) The mechanical losses include the friction between the rotating armature shaft and its journal bearings and the friction of the brushes upon the commutator. These friction losses are practically the same at all loads, and consume a certain percentage of the power supplied to the machine, which does not therefore appear as useful energy in the external circuit.

(2) The electrical losses include the I^2R losses in the armature and fields, the losses due to eddy currents, ¶ 332 and hysteresis, ¶ 336. All the losses may be summed up then as due to,

(*a*) *Mechanical friction,*
(*b*) *Electrical friction* (*resistance*),
(*c*) *Magnetic friction* (*hysteresis*).

344. Efficiency of a Dynamo.—The meaning of the term efficiency is given in ¶ 227. There are two efficiencies of a dynamo,

(*a*) *Electrical efficiency,*
(*b*) *Commercial efficiency.*

(a) ELECTRICAL EFFICIENCY.—Electrical efficiency is the ratio of the electrical energy delivered to the external circuit to the total energy generated. The total electrical energy generated is equal to the energy delivered to the external circuit plus the I^2R loss in the armature and the I^2R loss in the fields or,

By Formula (84) $\text{Eff.} = \dfrac{W}{W + w}$,

when $W =$ useful electrical energy,
and $w =$ energy lost in the machine.

TO OBTAIN THE ELECTRICAL EFFICIENCY OF A DYNAMO:

Find the sum of the energy delivered, the loss in the armature

*coils, and the loss in the field coils, and divide the energy delivered by this sum.**

Let W = useful or available energy;
w = loss in armature (I^2r);
w_1 = loss in field coils (I^2r).

$$\text{Then,} \qquad \text{Elec. Eft.} = \frac{W}{W + w + w_1} \quad . \quad . \quad . \quad . \quad (102).$$

Prob. 122: A dynamo delivers 40 K.W. to an external circuit and there is .6 K.W. lost in the field coils and 1 K.W. lost in the armature. What is the electrical efficiency?

$$\text{By Formula (102) Elec. Eff.} = \frac{W}{W + w + w_1} = \frac{40}{40 + 1 + .6} = .96 = 96 \text{ per cent.}$$

$W = 40$ K. W., $w = 1$ K. W., $w_1 = .6$ K.W.

The electrical efficiency varies with the size of the dynamo; a 1-K. W. dynamo may have as low an efficiency as 50 per cent; a well designed 40-K. W. dynamo, 96 per cent, and generators of several thousand K.W. 98 per cent or more.

(b) COMMERCIAL EFFICIENCY.—Commercial efficiency is the practical rating of the machine and is the ratio of the energy delivered by it to the energy supplied to it, or,

$$\textbf{Commercial Efficiency} = \frac{\textbf{Output}}{\textbf{Intake}}.$$

Commercial efficiency therefore includes the mechanical, electrical, and magnetic losses given in ¶ 343. The commercial efficiency is always less than the electrical efficiency and varies with the size of the machine and the load it is supplying. For example, a 40-K.W. generator has an electrical efficiency of 96 per cent, while the commercial efficiency is,

at ¼ overload	89	per cent
at full load	91	"
at ¾ load	89	"
at ½ "	87	"
at ¼ "	84	"

TO OBTAIN THE COMMERCIAL EFFICIENCY:

Divide the energy delivered by the dynamo by the sum of the mechanical, electrical, and magnetic losses.

*The eddy currents and hysteresis losses are usually included in the mechanical losses since there is no direct method of measuring them.

Formula (84) applies to the commercial efficiency.

Prob. 123: It requires 44 K.W. (58 H. P.) to drive the 40-K.W. dynamo mentioned in Prob. 122. What is its commercial efficiency?

By Formula (84) Com. Eff. $= \frac{W}{W + w} = \frac{40}{44} = .90 = 90$ per cent.
$W = 40$ K. W., $W + w = 44$ K. W.

QUESTIONS.

1. What is meant by laminating an armature core? Why is this necessary?
2. State three ways in which energy is unavoidably and uselessly expended in the internal actions of a dynamo.
3. What are the neutral points of a dynamo?
4. Locate the neutral points in a bipolar dynamo when the armature rotates against the hands of a clock.
5. What is the hysteresis loss in a dynamo?
6. Sketch the position of a pair of brushes properly set upon a 48-part commutator in a two-pole field.
7. Why should a coil be commutated as it passes through the neutral point?
8. Sketch the position of brushes properly set upon an 8-pole armature having 192 segments.
9. Since a two-part commutator is so simple in construction, why are armature windings sub-divided into many coils, thus necessitating many commutator bars?
10. In some dynamos it is necessary to change the position of brushes for changes in the current flowing from the machine. Why is this?
11. State some causes for sparking at the brushes of a dynamo.
12. A piece of mica subjected to an insulation test is said to have broken down at 4500 volts. What is meant by this?
13. A ring armature contains a defective coil. How would you temporarily remedy the trouble so that the machine could be operated?
14. What is the difference between the electrical and commercial efficiency of a dynamo?
15. Explain what determines the capacity of a dynamo.
16. The electrical efficiency of a 180-K. W. dynamo is 90 per cent. How much electrical energy is developed? *Ans.* 200 K. W.
17. If it requires 325 H. P. to drive the dynamo in question 16, what is its commercial efficiency? *Ans.* 74 per cent.

LESSON XXVIII.

DIRECT CURRENT DYNAMOS.

Bipolar Field Magnets—Multipolar Field Magnets—Multipolar Field Armature Circuit—Constant Current and Constant Potential Dynamos—Classification of Dynamos According to their Field Excitation—The Self-Exciting Principle of Direct Current Dynamos—Residual Volts—The Shunt Dynamo (Constant Potential) —Action of the Shunt Dynamo—Action of the Series Dynamo (Constant Current)—Compound Machines (Constant Potential) —Compound Wound Dynamos in Parallel–The Equalizer—Questions and Problems.

345. Bipolar Field Magnets.—In the smaller size of dynamos employing a two-pole or bipolar field, the magnetic circuit has been designed in a variety of forms; the horseshoe type of field, as used in the Edison bipolar dynamo; the inverted horseshoe type, Fig. 303, used in the Crocker-Wheeler and other makes, and the Manchester type of fields are very common forms. In the inverted horseshoe type the winding may be either upon the yoke as A, Fig. 355, or upon each limb, as C, in the same figure. The yoke thus serves as a bed-plate for the machine as well as to conduct the magnetic lines of force. In the Manchester pattern there is a closed magnetic circuit, B of Fig. 355, also Fig. 356. The

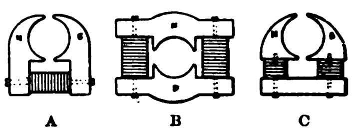

Fig. 355.—Bipolar Field Magnets.

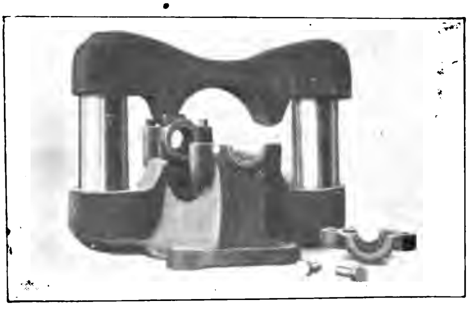

Fig. 356.—Manchester Type of Field Frame.

yokes are cast iron, the lower one forming the bed-plate, and the magnet cores are of soft wrought iron. The magnet coils are connected so that the upper end of each limb tends to produce the same pole, a *consequent pole* is thus formed in each yoke, and the lines of force pass from yoke to yoke across the gap in which the armature is inserted. The direction of the magnetic lines of force is depicted in Fig. 357.

346. Multipolar Field Magnets.—The objection to a bipolar field is, that with a dynamo of large output the speed at which its armature would have to rotate to generate commercial voltages, would be prohibitive from a mechanical standpoint. By arranging a number of electromagnets with their poles extending inward from an iron ring, forming a multipolar field ring, the conductors upon the armature, revolving between them, cut the magnetic lines of force many more times in one revolution, so that, as the size of the machine increases the speed decreases. Slow speed is an advantage in any apparatus with moving parts, because there is less liability of derangement, less wear, and hence less need of frequent renewal of such parts. If a two-pole 45-K. W. dynamo is required to run at 1000 revolutions per minute to generate an E. M. F. of 125 volts, a four-pole dynamo of equal output will run at only 500 revolutions; one of eight poles, at only 250 revolutions per minute. Many four-pole field yokes are octagonal, but when more poles are required the ring form is used. The field magnet cores are generally cylindrical in form and constructed of cast "mild" steel (soft steel) containing a very small percentage of carbon, the magnetic quality of which is nearly equal to that of wrought iron This is a much cheaper construction than where they are forged from wrought iron. The wrought iron or cast steel cores are cast-welded into the plain cast iron field ring, which, in the larger sizes, is generally divided into two parts,

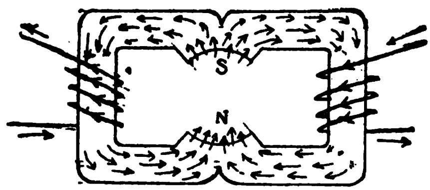

Fig. 357.—Magnetic Circuit of Manchester Field Frame.

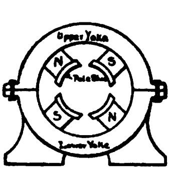

Fig. 358.—Multipolar Field Ring.

for convenience in handling. The coils are wound in the lathe, upon cast brass bobbins, which can be slipped directly over the cores and fastened in place by bolts. Joints should be omitted in the magnetic field circuit for the reason given in ¶ 198, and all sharp corners, bolts, etc., should be rounded to prevent magnetic leakage.

347. Multipolar Field Armature Circuits.—The circulation of current through the windings of a ring armature rotating in a four-pole field is shown in Fig. 359. The direction of rotation is clockwise, and the direction of current through the windings under any particular pole can be found by Fleming's Rule, ¶ 278. The currents in the windings under the upper **N** and **S**-poles are opposed to each other and flow to the external circuit by the + brush 1 and back to this half of the armature by — brushes 3 and 4. At the same instant the opposed currents in the lower windings flow to the external circuit by + brush 2 and return to the armature through — brushes 3 and 4. The armature is thus divided into four circuits and four brushes are required and must be placed between the poles so as to short-circuit the coils as they pass through the neutral space. In this form of winding there is no difference of potential between the + brushes, so that they are connected in parallel, as are also the negative brushes, and then to the external circuit. In multipolar machines there are as many brushes as pole pieces,* and all the + brushes are generally connected to one main generator cable, forming the + terminal of the machine, and likewise to the negative brushes.

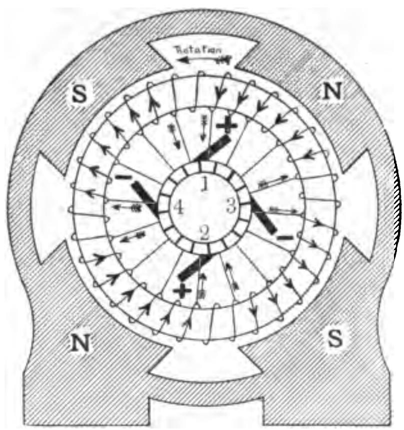

Fig. 359.—Direction of Current Through the Windings of a Ring Armature Rotating in a Four-Pole Field.

*Since opposite commutator bars are of the same potential on this four-pole dynamo they may be joined by a cross-connecting wire and two brushes, as 2 and 4, dispensed with. This can only be done when there is an even number of coils. The armature is said to be "cross-connected."

348. Constant Current and Constant Potential Dynamos.—Alternators and direct current dynamos may be classified according to their design as follows :

(*1.*) *Constant potential dynamos,*
(*2.*) *Constant current dynamos.*

With *constant potential dynamos* the voltage is maintained constant across two or more parallel mains in which the current varies according to the resistance of the multiple circuit. Incandescent lighting, indoor arc lighting, motors and street railway systems are operated from *multiple circuits* connected to constant potential generators. In a *constant current dynamo* the current is maintained constant through an external series circuit connected to it, while the E. M. F. varies with each change in the resistance of the circuit. Street arc lamps are operated in series from constant current machines. The strength of the current is usually 9.6 amperes and the voltage may vary from 45 to 8000 volts according to the number of lamps in circuit. The reason for operating these lamps in series is that they are generally distributed over a very large area, and a great economy in copper is effected by employing a small wire, generally about No. 6, for the series circuit and using a high voltage. The distribution of voltage throughout the circuit is much more uniform than would be possible with a multiple system, so that all the lamps regulate properly.

349. Classification of Dynamos According to Their Field Excitation.—The current for magnetising the field magnets of a dynamo may be supplied from a separate generator or by the machine itself, when it would be styled either a *separate* or *self-exciting* dynamo. The methods of *excitation* are, of course, independent of the field construction and depend only upon the connections. A *compound wound* machine is one in which the method of exciting the field magnets is a combination of two simple methods. Dynamos may be classified according to the methods used to excite the field magnets as follows :

1. Simple Machines.—

(a) Magneto Machines, Fig. 318.—The field magnets are permanent magnets and the machine used only for signalling or testing. It may give D. C. or A. C. currents.

(b) SERIES MACHINES, A, FIG. 360 (*Constant Current*).—The field magnets are connected in series with the armature and wound with a few turns of heavy wire having a low resistance, so as not to oppose the main current flowing through them.

(c) SHUNT MACHINES, B, FIG. 360 (*Constant Potential*).—The field magnets are connected in parallel or shunt with the armature and are wound with many turns of small wire having a high resistance, compared with the armature, since only a small portion of the main current flows through them.

(d) SEPARATELY EXCITED MACHINES, D, FIG. 360 (*Constant Potential*).—Current for the field magnets is supplied from a separate dynamo.

2. Compound Machines.—

(e) SERIES AND SHORT SHUNT MACHINES, F, FIG. 360 (*Constant Potential*).—The field cores contain two independent spools. One is wound with a few turns of heavy wire, forming the *series coil* and connected in series with the main circuit, the other, with a great many turns of smaller wire, forming the *shunt coil* and connected in shunt with the armature.

(f) SERIES AND LONG SHUNT MACHINES, G, FIG. 360 (*Constant Potential*).—The same as (e) except that the shunt field shunts not only the armature but also the series field; hence it is called a *long shunt.*

3. Alternating Current Machines.—

(g) SEPARATELY-EXCITED MACHINES, D, FIG. 360 (*Constant Potential*).—The field magnets are excited from an auxiliary dynamo called an *exciter*. Alternators require an exciter, since the alternating current cannot be employed to excite the fields. The exciter may be either a separate dynamo or an independent direct current winding upon the alternator shaft, Fig. 360, H.

(h) SEPARATE COIL, SELF-CONTAINED MACHINES, C, FIG. 360.—Separate coils wound on the armature core are connected to an independent commutator, which furnishes current for the field magnets.

(j) SERIES AND SEPARATELY-EXCITED MACHINES, E, FIG. 360.—Two independent field windings correspond to the series

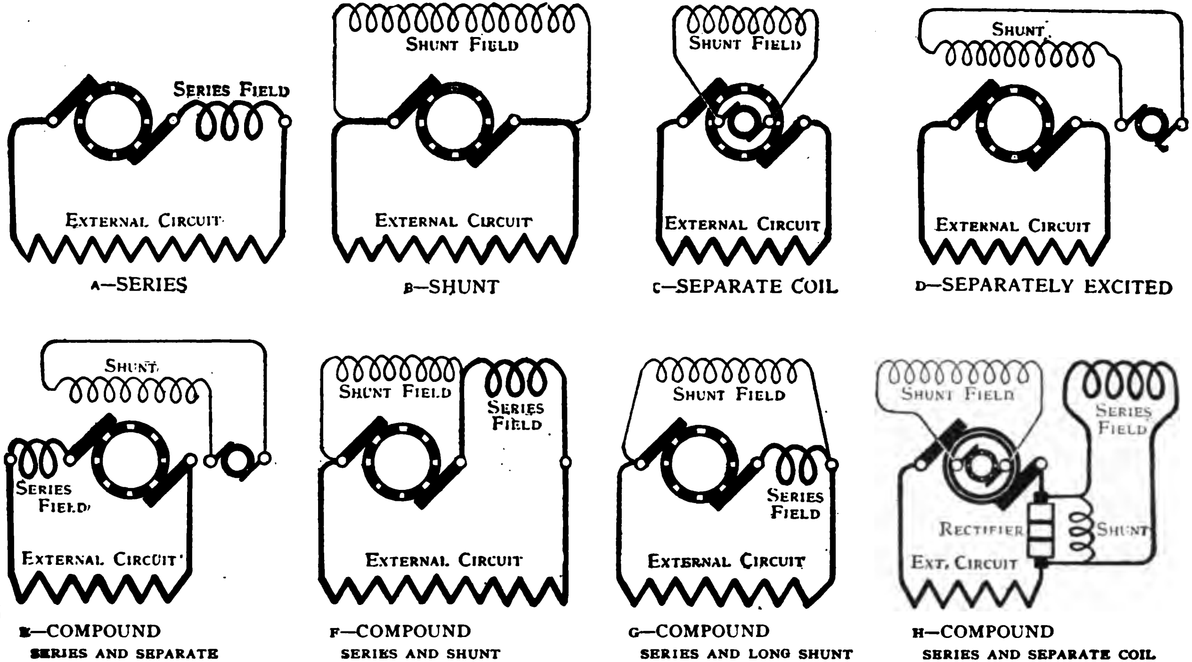

Fig. 360.—Classification of Dynamos According to the Method of Exciting the Field Magnets

and shunt coils of F. The shunt coil is supplied from an exciter, while the main current, commuted, flows through the series field coils. This method is employed in *composite* wound alternators, a portion of the main alternating current is commuted by a special device called a *rectifier*, located on the armature shaft. Its function is to change that portion of the alternating current intended for the series coils, into a direct current for producing the magnetisation. A self-contained separate coil alternator, composite wound, is depicted in H, Fig. 360. Details of the principal types are given in the paragraphs which follow.

350. The Self-Exciting Principle of Direct Current Dynamos—Residual Volts.—In very early dynamos the field magnets were always separately excited by either a battery or magneto machine. With the discovery of residual magnetism, ¶ 30, their self-exciting principle was recognized. If the soft iron or steel cores of a dynamo have once been magnetised they retain permanently a small amount of their magnetism. An armature revolving in even so weak a field as that due to residual magnetism will cut some lines of force, and as a result there is an E. M. F. maintained at the brushes without any excitation. This is often spoken of as the *residual volts*, and will be indicated upon a voltmeter connected to the brushes, when the field circuit is open, and the armature revolves at its proper speed. This E. M. F. may be from 2 to 10 volts or more, depending upon the quality of the iron, the number of armature conductors, etc. If now the field circuit be connected to the brushes, a current will flow through the field magnets due to the residual volts; the number of lines of force of the field increases with this increase in field strength; the induced volts also increase and cause additional current to flow around the fields, resulting in a further increase of voltage at the brushes. This action continues until the maximum voltage of the machine is attained. The process has been termed "the building up of the fields," and may be noted either on a voltmeter, or by the gradual increase in the brilliancy of a lamp connected to the brushes, called a *pilot lamp*, when any direct current dynamo starts to generate. Ten to twenty seconds may be required from the time the field switch is closed until the armature generates its full voltage. A machine may refuse to build up, owing to the loss of its residual magnetism, when the cores should be remagnetised.

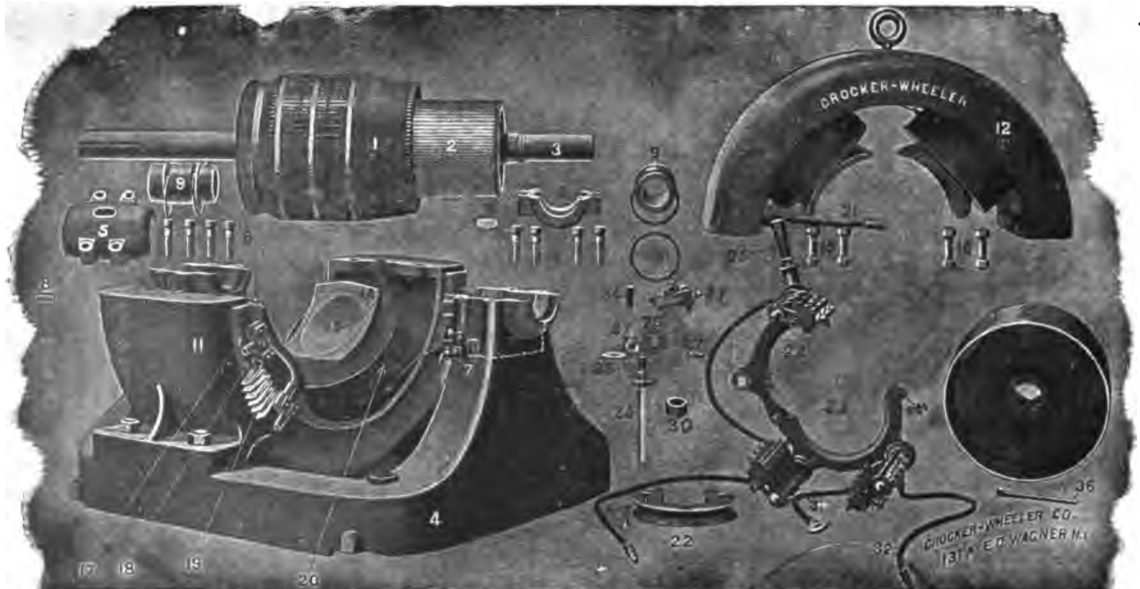

Fig. 361.—Dissected Multipolar Dynamo.

1. Armature (includes 2 and 8).
2. Commutator.
3. Shaft.
4. Base.
5. Bearing cap.
6. Bearing cap screws.
7. Oil cock.
8. Oil hole cover.
9. Journal box.
10. Oil ring.
11. Lower magnet frame (includes 13 and 14).
12. Upper magnet frame (includes 13 and 14).
13. Pole.
14. Pole shoe.
15. Eye bolt.
16. Magnet frame bolt.
17. Terminal board,
18. Terminal block.
19. Compounding shunt.
20. Field coil.
21. Field cable.
22. Rocker seat with screws.
23. Brush rigging (includes 24 to 34).
24. Rocker (includes 25).
25. Rocker handle.
26. Brush stud.
27. Brush stud nut.
28. Brush stud insulating washer (round hole).
29. Brush stud insulating washer (oval hole).
30. Brush stud insulating sleeve.
31. Brush stud cable.
32. Armature cable.
33. Brush holder.
34. Brush.
35. Pulley.
36. Pulley key

Prob. 124: The resistance of the armature of a dynamo is .15 ohm and that of the field magnets, 100 ohms. With open fields the armature generates 6 volts, due to the residual magnetism. What current will flow around the field to start the building-up process when the field circuit is closed?

By Formula (31) $I = \frac{E}{R + r} = \frac{6}{100 + .15} = .059$ ampere.

351. The Shunt Dynamo—*Constant Potential.*—In a shunt dynamo, Fig. 362, the field coils are of comparatively high resistance as compared with the armature; for example, the multipolar field of a 125-volt, 11-K. W. dynamo has a resistance of about 40 ohms, and the armature resistance is only .095 ohm. The field ampere-turns of a shunt dynamo are the product of a very small current and a great many turns, so that little of the electric energy generated will be used for their excitation. The regulation of the voltage in the external circuit of a shunt machine is accomplished by varying the current through the field coils, by means of a resistance inserted in series with them, and called the *field rheostat*, Fig. 363. Decreasing the resistance in the field rheostat increases the current around the field coils, thereby increasing the ampere-turns, the number of lines of force cut by the armature, and the induced volts at the brush terminals. Inserting resistance in the field rheostat lowers the voltage at the brushes.

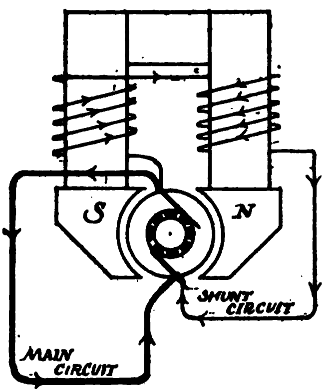

Fig. 362.—Shunt Dynamo.
The field magnets are connected across the brushes. B—Fig. 360.

The current flowing through the shunt field is equal to the potential difference at the brushes, divided by the resistance of the field plus the resistance in the field rheostat, Formula (28).

The current flowing through the armature of a shunt dynamo is the sum of the currents in the field circuit and in the external circuit. The volts drop in the armature is equal to its resistance multiplied by the current flowing through it, Formula (29).

The resistance of the armature is usually measured by the drop method, ¶ 241, and will be higher after the machine

has been carrying a load for some time, on account of the heating effect.

352. Action of the Shunt Dynamo.—In starting a shunt dynamo, after proper speed is attained, the machine is brought up to the required voltage by the field rheostat, and then the main switch connecting it with the external circuit is closed. Suppose that the voltmeter indicates 112 volts potential difference when the external circuit is open. The E. M. F. will be a little higher than this value and equal to $112 + I \times r$, where I equals the current through the fields and r equals the armature resistance. A voltmeter, therefore, placed across the brushes of any self-exciting dynamo indicates the potential difference rather than the E. M. F. If the field rheostat is adjusted for any particular voltage with the main circuit open, say 112 volts, and the switch is now closed so that more current flows from the armature, the voltmeter at once indicates a lower voltage, say 108 volts. If the speed is the same as before, this loss is due to two causes: *first*, there is an increased drop in the armature due to the additional current flowing through it, which lowers the potential difference at the brushes; *second*, the potential difference at the brushes being lowered, less current flows around the field, so that there are not quite so many lines of force cut as before. When the load is switched on to a shunt dynamo, the resistance in the field *rheostat* must therefore be *diminished* so that the voltage will be raised to its former value.

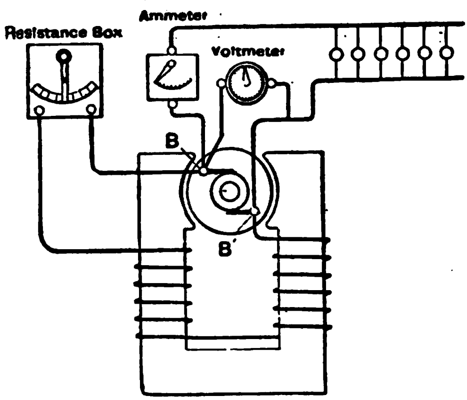

Fig. 363.—Regulating the E. M. F. at the Brushes of a Shunt dynamo by the Shunt Field Rheostat.

Again, in the above case, if after the voltage is raised from 108 to 112 volts the load be disconnected, the voltmeter will indicate a higher voltage than 112 volts, say 116, and resistance must now be *inserted* in the field *rheostat* to lower the

voltage. The potential difference at the brushes thus varies in a shunt dynamo, with each change in load, *increasing as the load decreases and decreasing as the load increases.* If the current fluctuations are wide and quite frequent, as on trolley lines where the cars are started and stopped so often, an attendant would be constantly required to manipulate the rheostat, or some automatic device employed for this purpose, so that this machine is not suitable for such work. Shunt dynamos are adapted to cases where the load is constant when they will require very little attention after the proper regulation has been made; they are classified as constant potential dynamos and may be connected in parallel when

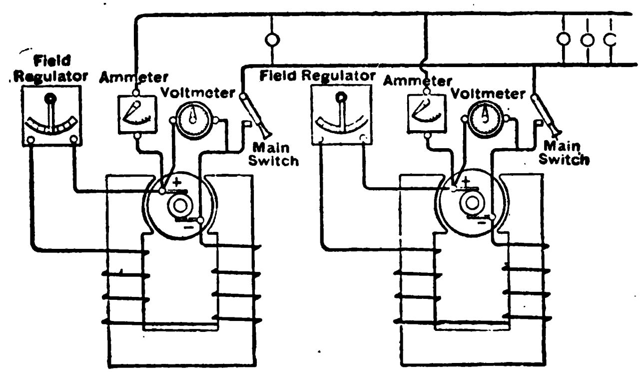

Fig. 364.—Two Shunt Dynamos Connected in Parallel.

The voltage across the mains is equal to that of one machine, the maximum current on the mains, equal to the sum of that of the two machines.

their voltages are equal. Shunt dynamos may be connected in parallel by connecting the positive and negative brushes as in Fig. 364. The voltage is the same as with one machine, but the current output will be the sum of the currents each machine can furnish separately. The voltage of the machine, to be paralled with other dynamos, should be adjusted equal to, or a little higher than their potential, when it can be connected to the common circuit. Such machines are practically self-adjusting to load conditions. If one machine runs a little faster than the rest it will do more work, and vice versa. Shunt dynamos will also operate in series, but if the machines are of different sizes, the current in the external cir-

cuit is limited to the capacity of the smaller machine. The polarity of the brushes of a shunt dynamo may be changed by either reversing the field connections to the brushes, or by reversing the direction in which the armature rotates. In the latter case the brushes will also have to be changed to agree with the direction of rotation.

Exp. 94: The following test, No. 1, was made upon a 1.25-K. W. shunt wound dynamo and illustrates the falling of potential at the brushes as the load increases. The voltmeter was placed across the brushes, the ammeter, in series with some lamps joined in parallel, and the shunt field rheostat adjusted so that the E. M. F. was 110 volts with no load. The rheostat was *not adjusted* thereafter during the test.

Test No. 1. **Test No. 2.**

Speed	Volts at brushes	Amperes	Speed	Volts at brushes
1540	110	1	2110	100
"	106	2	2200	104
"	103	3	2290	108
"	100	4	2380	112
"	98	5	2470	116

Exp. 95: The above test, No. 2, illustrates how the induced volts vary proportionally with the speed. The field magnets were separately excited so that the lines of force cut were the same at all speeds.

Prob. 125: A shunt dynamo, Fig. 365, maintains 110 volts across 100 incandescent lamps joined in parallel, requiring 55 watts and 110 volts each. The lamps are located 100 feet from the dynamo and the resistance of the leads is .02 ohm; 6.5 K. W. are required to drive the dynamo. Resistance of armature .03, and fields 37 ohms. Find the following:

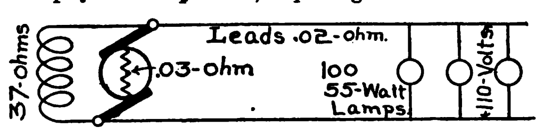

Fig. 365.—E. M. F. and P. D. of a Shunt Dynamo.

(a) P. D. at brushes; (b) total E. M. F. generated; (c) watts lost in the armature; (d) in the field; (e) in the leads; (f) in the lamps. (g) What is the electrical efficiency? (h) What is the commercial efficiency?

By Formula (63) $I = \frac{W}{E} = \frac{55}{110} = \frac{1}{2} \times 100 = 50$ amperes for lamps.

(29) $E = I \times R = 50 \times .02 = 1$ volt drop in leads.

$110 + 1 = 111$ volts P. D. at brushes (a).

(28) $I = \frac{E}{R} = \frac{111}{37} = 3$ amperes through the fields.

$50 + 3 = 53$ amperes through the armature.

(29) $E = I \times R = 53 \times .03 = 1.59$ volts lost in armature.

$1.59 + 111 = 112.59$ volts total E. M. F. (b).

(62) $W = E \times I = 1.59 \times 53 = 84.27$ watts lost armature (c).

$111 \times 3 = 333$ watts lost in fields (d).

$1 \times 50 = 50$ watts lost in leads (e).

$110 \times 50 = 5500$ watts lost in lamps (f).

(102) Elec. Eff. $= \frac{W}{W + w + w_1} = \frac{5500 + 50}{5550 + 84.27 + 333}$
$= .93 = 93$ per cent (g).

(84) Com. Eff. $= \frac{W}{W + w} = \frac{5550}{6500} = .85 = 85$ per cent (h).

353. Action of the Series Dynamo (*Constant Current*).—In a series dynamo, Fig. 366, the field coils are in series with the armature, and have a low resistance, since the current from the armature flows through them to the external circuit.* The field ampere-turns of a series dynamo, as distinguished from the shunt machine, are the product of a much larger current and a less number of turns. With the armature running at a constant speed, the E. M. F. and current from a series dynamo will vary with every change in the resistance of the external circuit, since each change of current alters the field magnetising current, and consequently, the E M. F. induced in the armature. In practice the current from a series dynamo is required to be constant, irrespective of the resistance of the external circuit, while the voltage is altered to suit the conditions of the circuit. It is thus a *constant current dynamo*. The regulation is accomplished by either of two general methods. In the first

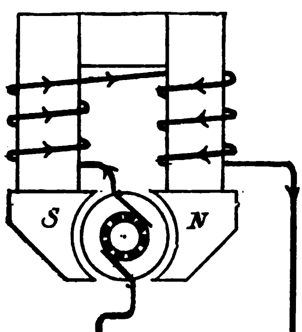

Fig. 366.—Series Dynamo.
The fields are in series with the armature. A—Fig. 360.

*For example, the field magnets of a 160-light Brush series arc dynamo have a resistance of 17.2 ohms and the armature for the combination given in ¶ 331, has a resistance of 18 ohms. The loss in the armature is thus nearly the same as in the field.

method the armature used is of the open coil type, ¶ 331, and the position of the brushes is automatically moved so as to be in connection with the armature coils while they are passing through any stage of induction, from the points of maximum induced E. M. F. to the minimum, or neutral points. Any change in the current strength tending to change the field magnetism is thus neutralized by a corresponding opposite change in the E. M. F. The automatic regulator is usually a solenoid and core attached to the brushes and actuated by the main current. This method is utilized in the Thomson-Houston arc light dynamo. In the second method an adjustable rheostat is placed in shunt with the series field magnets, Figs. 366, 367, and the main current divides in proportion to the resistances of the two circuits. The arm of the rheostat is automatically moved by a solenoid and core arrangement actuated by the main current. If the resistance of the external circuit is suddenly lowered, the increased current immediately actuates the solenoid and rheostat arm in a direction to decrease its resistance, thereby shunting more current from the field circuit, and preventing the rise of E. M. F. When the external resistance is increased the resistance in the rheostat is automatically increased and more current flows around the field magnets, thus increasing the E. M. F. This second method is used in the Brush arc light generator. Obviously a series dynamo will not self-excite when the external circuit is open, and will not "build up" when the external resistance is very high. This may be overcome by momentarily short-circuiting the machine while the external circuit is closed, when the E. M. F. will rise to a sufficient value to start the action. With a sensitive automatic regulator a series machine may be short-circuited without injury, since the larger current which

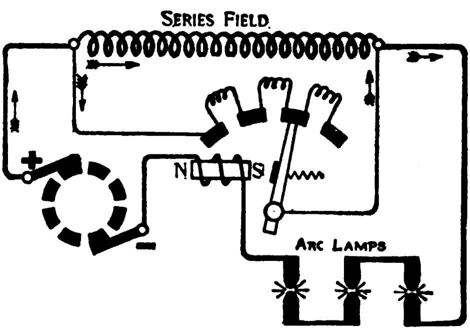

Fig. 367.—Regulating the Voltage of a Series Dynamo by Shunting the Series Field.

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would tend to flow, immediately actuates the automatic mechanism in such a manner as to decrease the E. M. F.

354. Compound Machines (*Constant Potential*).—The compound wound dynamo is designed to automatically give a better regulation of voltage on constant potential circuits than is possible with a shunt machine, and possesses the characteristics of both the series and shunt dynamos. The shunt field is the same as in the shunt dynamo, and independent series field spools are added, through which the main current flows. These are connected so as to increase the magnetism of each pole produced by the shunt winding, Fig. 368. With no current in the external circuit the machine separately excites by its shunt field. When current flows to the external circuit the voltage at the brushes is not lowered, as in the shunt dynamo, since the series winding strengthens the field by the current flowing through it, and thus raises the voltage in proportion to the increased current. By a proper selection of the number of turns in the series coils, the voltage is thus kept automatically constant for wide fluctuations in load

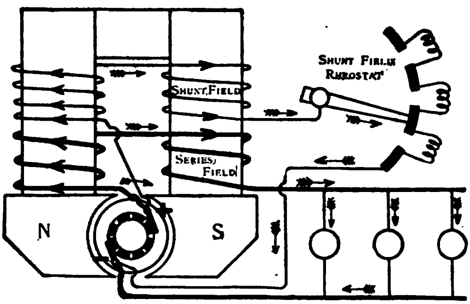


Fig. 368.—Compound Wound Dynamo.
The series and shunt field act in unison. F—Fig. 360.

without changing the shunt field rheostat. If a greater number of turns is used in the series coil than required for constant voltage at all loads, the voltage will rise as the load is increased, and thus make up for the loss on the transmission lines, so that a constant voltage will then be maintained at some distant point from the generator. The machine is then said to be *over-compounded*. This over-compounding is usually designed for a rise of voltage from 5 to 10 per cent of that of the machine, from no load to full load. In design, the field coils are wound with a greater number of turns than actually required, and the machine is accurately compounded by a running load test after completion. These adjustments are made by placing a German

silver shunt in parallel with the series field so that the main current divides between the two circuits, Z, Fig. 371; also 19, of Fig. 361. The length of the shunt can then be regulated to send sufficient current around the series coils to produce the desired compounding. In a short shunt compound wound generator the shunt field is subjected to a higher voltage than in the long shunt connections. The E. M. F. applied to the shunt field in the latter case for any particular load, being equal to the E. M. F. at the brushes minus the drop on the series field, F and G of Fig. 360. Compound wound direct current dynamos are used in incandescent electric light-

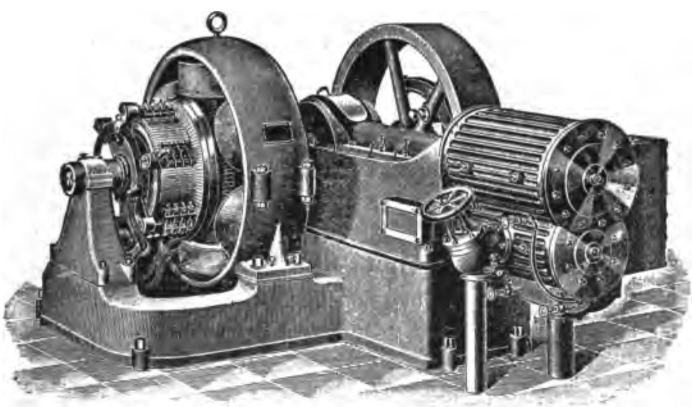


Fig. 369.—100-K. W. 125-Volt Multipolar Compound Wound D. C. Dynamo Direct-connected to a Steam Engine.

Output at brushes, 800 amperes at 125 volts. Speed, 270 revolutions. Poles, 6. Approximate horse power required to drive generator, 150 H. P. Approximate weight: armature and commutator, 2,950 pounds; generator complete, 11,200 pounds.

ing stations and in electric railway power stations where the load is very fluctuating. A short circuit on a compound wound dynamo overloads the machine, since the excessive current flowing through the series field tends to keep the voltage at its normal value. Unless the line is automatically opened under such a condition either by a fuse or circuit breaker, the machine and its driving engine will be damaged. To avoid heavy short circuits, which would damage such generators as well as their engines, they are protected by automatic circuit breakers, Fig. 176.

Exp. 96: The following test was made on the 1.25-K. W. dynamo, referred to in Exp. 94. The series field was short-circuited in the previous tests. Both fields are acting in the present case. The machine was adjusted to 110 volts by the shunt field rheostat as before, and *not changed* during the test. It will be noted that the potential is constant whether 1 lamp or 5 lamps are in circuit. Compare with the shunt dynamo test in ¶ 352.

Compound-Wound Dynamo Test.

Speed.	Volts at Brushes	Amperes.
1540	110	1
1540	110	2
1540	110	3
1540	110	4
1540	110	5

Prob. 126: A compound wound dynamo supplies 100 amperes at 112 volts to a group of lamps located 75 feet from the generator. Resistance of leads .02 ohm; armature .01 ohm; series coil .02 ohm; shunt coil 40 ohms; 14 K. W. are required to drive the machine, Fig. 370. Find the following:

(a) P. D. at brushes; (b) total E. M. F. generated; (c) watts lost in the leads; (d) in the series; (e) in the shunt; (f) in the armature; (g) in the lamps. (h) What is the electrical efficiency? (k) What is the commercial efficiency?

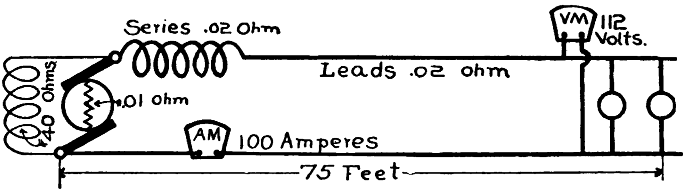


Fig. 370.—E. M. F. and P. D. of a Compound Wound Dynamo.

By Formula (29) $E = I \times R = 100 \times .02 = 2$ volts drop in leads

$112 + 2 = 114$ volts P. D. at terminals.

(29) $E = I \times R = 100 \times .02 = 2$ volts drop on series field.

$114 + 2 = 116$ volts P. D. at brushes (a).

116 volts across shunt field.

(28) $I = \frac{E}{R} = \frac{116}{40} = 2.9$ amperes through shunt field.

$100 + 2.9 = 102.9$ amperes, total current through armature.

(29) $E = I \times R = 102.9 \times .01 = 1.029$ **volts drop in armature.**

E. M. F. $= 112$ volts (lamps) $+ 2$ volts (leads) $+ 2$ volts (series) $+ 1.029$ volts (armature) $= 117.029$ volts (b).

(68) $W = I^2R = 100 \times 100 \times .02 = 200$ **watts** (c);

$= 100 \times 100 \times .02 = 200$ **watts** (d);

$= 2.9 \times 2.9 \times 40 = 336.4$ **watts** (e);

$= 102.9 \times 102.9 \times .01 = 105.884$ **watts** (f).

(62) $W = E \times I = 114 \times 100 = 11400$ **watts external circuit** (g).

$117.029 \times 102.9 = 12042.28$ **watts generated.**

$$(102)\ \text{Elec. Eff.} = \frac{W}{W + w + w_1} = \frac{11400}{12042.28} = .94$$

$= 94\%$ (h).

$$(84)\ \text{Com. Eff.} = \frac{W}{W + w} = \frac{11400}{14000} = .81 = 81\%\ (\text{k}).$$

355. Compound Wound Dynamos in Parallel—The Equalizer.—Compound wound dynamos are generally run in parallel, but more care must be exercised in connecting them in circuit than with the shunt machine. In order to connect several compound wound dynamos in parallel a special regulating device, called an *equalizing bar* must be used. The function of this equalizer is to enable each machine to take its share of the load and to make the load on the machines so paralleled, independent of slight changes in speed. The equalizing bar, Fig. 371, connects the brush of one dynamo, to which the series field is attached, to the corresponding brush of another dynamo. Both brushes, so connected, are of the same polarity and also of the same potential when the machines run at the same voltage. The action is as follows: suppose the compound wound dynamo No. 1, Fig. 371, is carrying a load and it is desired to parallel machine No. 2 with it; the latter is brought up to speed and its voltage regulated by the shunt field rheostat till a voltmeter indicates that it is equal to that of No. 1. Though the terminals of the loaded and free machines are now equal in voltage the voltage at the brushes of the loaded machine will be higher than that of the other, by an amount equal to the drop on the series field of No. 1. There is thus a difference of potential between the two ends of the equalizing bar, and when this switch (E) is closed, some current flows

through the equalizer and around the series field of machine No. 2 to the external circuit. The line switch S^2 is now closed and the free machine takes some portion of the load and is further regulated by its shunt field rheostat. When complete equalization of load occurs there will be no current in the equalizer. If the speed of either machine falls, thereby lowering its voltage, current from the other machine will flow through the equalizer and strengthen its series field, thus increasing the voltage. There is thus sometimes no current in an equalizer while at other times it may be flowing in either one direction or the other. To reduce the I^2R loss, the equalizer should be as short as possible and as large

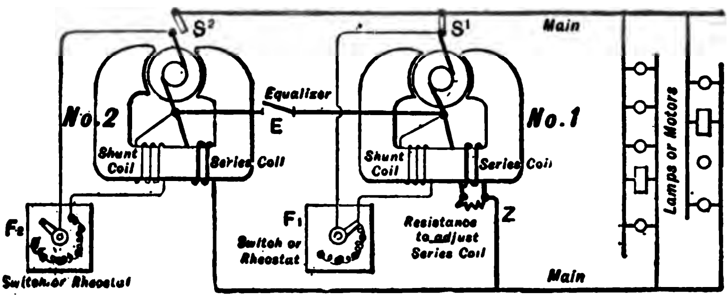


Fig. 371.—Two Compound Wound Dynamos Connected in Parallel.

as the main dynamo cables. A triple pole switch is generally used for coupling a compound dynamo with others, the middle blade of which is slightly longer than the other two, and is connected to the equalizer. When the switch is closed the equalizer is thus connected first, and the main terminals a little later. In shutting down a dynamo in parallel with others the main line terminals are first disconnected and then the equalizer, which is performed in one operation with the triple pole switch alluded to above. The voltage should then be lowered by inserting all the resistance of the shunt field rheostat in circuit, when this field circuit switch may be opened, and then the speed reduced. Any number of compound dynamos may be operated in parallel. If the machines are of different capacities they may also be run in parallel, provided that the voltages are the same, and resistances of the series fields made inversely proportional to the

current capacities of the several machines to be connected. Each machine will then take load in proportion to its capacity. The series fields can be adjusted by adding several turns of extra wire to this circuit, as required.

QUESTIONS.

1. Why are large dynamos constructed with multipolar rather than bipolar fields?
2. Sketch a ring armature located in a six-pole multipolar field, indicating the polarity of brushes and fields, and direction of current from the armature.
3. What is the distinction between constant current and constant potential dynamos?
4. What is a compound-wound dynamo?
5. Since the field magnets of a self-exciting dynamo are not supplied with current from any external source, how is it possible for the machine to generate?
6. A 110-volt incandescent lamp is connected to the terminals of a series machine running at its proper speed and capable of generating 4000 volts, yet the lamp fails to light. Why is this?
7. The main switch of a shunt dynamo is closed and then the machine started up, but it refuses to "build up." Why is this?
8. A large number of lights are suddenly switched off from a circuit connected to a shunt dynamo. What two actions will immediately occur at the generator and how will you counteract them?
9. What are "residual volts"?
10. Give two reasons for the fall of potential at the brushes of a shunt dynamo when the current from it is increased.
11. What is the advantage of a compound-wound generator over a shunt type of machine?
12. What is the difference in the method of regulating the field magnetising force of a series and shunt machine?
13. A generator is compounded for 10 per cent of its rated voltage. What is meant by this and how is it accomplished?
14. What is meant by an over-compounded generator?
15. Since an alternating current is not suitable for magnetising its field magnets, how can an alternator be self-exciting?
16. What is an exciter, and for what is it used?
17. What will be the effect of joining two shunt dynamos in series if one machine is rated at 45 K. W. and the other at 100 K. W? Both machines have the same E. M. F.
18. What is an equalizing bar, and for what purpose is it used?
19. How would you proceed to parallel a compound wound D. C. machine, which is "shut down," with two others carrying loads?
20. How would you disconnect and shut down one of the machines in question 19?
21. Make diagramatic sketches of all the different methods of field excitation with which you are familiar.

PROBLEMS.

1. A series dynamo has an armature resistance of .03 ohm; the field coils, .01 ohm; the machine is connected to an arc lamp requiring 14 amperes and having a resistance of 4 ohms; the resistance of the lead wires is .4 ohm. The machine requires 1½ H. P. to drive it. Find the following: (*a*) Total E. M. F. generated. (*b*) P. D. at the brushes. (*c*) Electrical efficiency. (*b*) Commercial efficiency. *Ans.* (*a*) 62.16 volts; (*b*) 61.74 volts; (*c*) 99 %; (*d*) 77 %.

2. A shunt dynamo is connected to 150 lamps, connected in parallel, each having a resistance of 60 ohms (hot), and requiring .85 ampere. The resistance of the armature is .02 ohm; field magnets, 22 ohms; leads neglected. (*a*) Find the E. M. F. (*b*) What is the P. D.? *Ans.* (*a*) 53.596 volts; (*b*) 51 volts.

3. A compound wound short shunt dynamo is connected to 700 incandescent lamps in parallel, each having a resistance of 220 ohms (hot) and requiring 110 volts. Resistance of leads, .02 ohm; shunt field, 40 ohms; series field, .015 ohm; armature, .025 ohm. It requires 70 H. P. to drive the machine. Find the following: (*a*) E. M. F. generated. (*b*) P. D. at brushes. (*c*) Drop on series field. (*d*) Watts lost in shunt field. (*e*) Watts lost on the line. (*f*) Electrical efficiency. (*g*) Commercial efficiency. (*h*) Make complete sketch. *Ans.* (*a*) 131.076 volts; (*b*) 122.25 volts; (*c*) 5.25 volts; (*d*) 373.565 watts; (*e*) 2450 watts; (*f*) 88 %; (*g*) 78 %.

4. The series coil of a short shunt compound dynamo, connected to 450 .6-ampere 100-volt lamps in parallel, is .009 ohm. The resistance of the leads is .2 ohm. (*a*) What is the P. D. at the brushes? (*b*) At the machine terminals? *Ans.* (*a*) 156.43 volts; (*b*) 154 volts.

LESSON XXIX.

DIRECT CURRENT MOTORS.

Comparison Between a Dynamo and a Motor—Principles of the Motor—Direction of Rotation of Series and Shunt Motors—Position of the Brushes on a Motor—Counter Electromotive Force of a Motor—Normal Speed of a Motor—Mechanical Work Performed by a Motor-Torque—Output and Rating of Motors—Moto Speed and Torque—Methods of Motor Speed Regulation—Speed Regulation of Series Motors (Second Method)—Series Motors for Railway Work—Operating Motors—Efficiency of a Motor—Electric Traction—Questions and Problems.

356. Comparison Between a Dynamo and a Motor.— A dynamo is a machine for generating electrical energy by moving conductors in a magnetic field, the force necessary to maintain the motion being supplied by a steam engine or other source of power. An electric motor is just the reverse of a dynamo, and is a machine for converting electrical power supplied to it into mechanical power at the motor pulley. When the field magnets of a dynamo, as Fig. 303, are excited and a current is passed through its armature by means of the brushes, the armature will revolve in the magnetic field. The rotation is due to the electrodynamic action between the magnetic field of the current-carrying wires upon the armature, and that produced by the field magnets. An electric motor, for direct currents, is constructed in the same manner as a dynamo. Any machine that can be used as a dynamo will, when supplied with electrical power, run as an electric motor, and conversely, an electric motor, when driven by mechanical power, will supply electrical energy to the circuit connected to it. Thus, a dynamo and motor are convertible machines, and the previous lessons upon the construction of dynamos will apply equally as well to the electric motor. Motors are classified in the same manner as dynamos and may be,

(a) *Series wound,*
(b) *Shunt wound,*
(c) *Compound wound.*

The fields may be either bipolar or multipolar, and since the number of poles determines the number of neutral points, there must be as many brushes as poles, except when the commutator is cross-connected, page 333.

357. Principles of the Motor.—The principles involved in the rotation of the armature conductors, when placed in a magnetic field, are fully discussed under the subject of electrodynamics, Lesson XXIII. It was there experimentally shown how a single loop, placed in a magnetic field, could be made to rotate, by commutating the current through it at the proper instant in a revolution, ¶ 275, and how the turning

Fig. 372.—Parts of a 20-H. P. Direct Current Slow Speed Motor.

K. W., 15. Volts, 250. Amperes, 60. Speed, 600 revolutions per minute. Average net weight, 2460 pounds. Diameter of pulley, 14 inches; face, 8 inches.

effort was increased by increasing the number of loops or coils and arranging them at different angles with reference to the field.* When the loops are angularly disposed around an iron core, as in a Gramme or drum ring armature, and then placed in a powerful magnetic field and a current passed through them, each loop tends to move to the position in which it encloses the greatest number of the lines of the field. The direction in which each loop will move will be such that its lines of force will be in the same direction as the

* The student is advised to again read ¶ 275.

lines of force of the field; the force with which it will move, or the turning effort or torque, ¶ 362, will depend upon the strength of current flowing through it (that is, the strength of current driving the motor), the size of the loop, and the density of the lines of force through it. When the loop arrives at the position where it accommodates the greatest number of the lines of force through it in the same direction as its own lines, the force, or turning effort, stops. If moved past this position the electrodynamic force is reversed and now tends to turn the coil back to the position of maximum lines of force through it. To obtain continuous rotation, the current through each loop must be reversed at the instant that the turning effort ceases. These reversals are automatically performed by the commutator. The drum or Gramme ring armatures fulfill these conditions, their commutators reversing the current through the coils at the proper instant, when the brushes are correctly set and adjusted.

In a dynamo the direction of current in the armature is such as to oppose the motion producing it, Lenz's Law; the reaction increased as the current from it increased, thereby requiring additional power to drive it as the load increased. The reaction of the current in the armature of a dynamo is thus opposed to the direction of rotation of the armature.

In a motor, the reaction of the magnetic field of the armature conductors upon the magnetic field surrounding them is such as to move the armature wires across the field in the same direction as the armature rotates, and it is this force which is used to perform mechanical work at the motor pulley. The greater the load applied to the pulley of a motor the greater will be this force or turning effort (torque), and consequently the greater the current taken by the motor armature from the supply mains.

358. Direction of Rotation of Series and Shunt Motors.—The direction of rotation of a motor, or that in which any dynamo will rotate when used as a motor, can be found by the left-hand rule, page 278, when the polarity of the field magnets and the direction of current through the armature have been ascertained. Place the left hand, as shown in Fig. 243, so that the fingers correspond with the polarity and direction of current in the single armature coil motor, Fig. 373, and it is found that the loop will rotate in the direction of the hands of a clock. The direction of rota-

tion of a motor can be changed by reversing the current either through the armature or through the fields, but not through both. If both are changed, the motor will run in the same direction as before. See page 279.

A series dynamo when supplied with current becomes a *series motor*, Fig. 366, and will run in the opposite direction to its motion as a generator. Reversing the direction of current at its terminals will not change the direction of rotation, since the current still flows through the armature in the same direction as through the field, Fig. 366. Reverse either the armature or field connections to change the direction of motion.

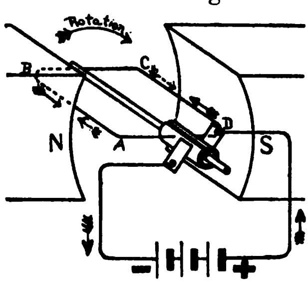


Fig. 373.—Single Loop Armature Driven as a Motor.

The dotted arrows indicate the direction of counter E. M. F.

A shunt dynamo runs in the same direction when used as a *shunt motor*, Fig. 362, as when used as a generator. This will be seen from Fig. 362; if the current, from an external source, enters by the lower brush it will flow up through the armature in the same direction as when it is used as a dyamo, but the current through the fields will be reversed from the direction indicated in the figure, since the fields are in parallel with the brushes.

Exp. 97: Connect the student's experimental dynamo, Fig. 309, as a shunt motor, Fig. 362; adjust the brushes so as to make contact with the *collector rings;* place the armature coil with its plane horizontal and pass a current through the motor. The coil is urged around until its plane becomes vertical, when rotation ceases, according to the principle outlined in ¶ 357. Incline the coil at any angle to the vertical position, and upon closing the circuit it rotates to the vertical position and stops.

Exp. 98: Now adjust the brushes upon the *two-part commutator* and repeat Exp. 97. The coil rotates continuously in one direction at several hundred revolutions per minute. The direction of current is reversed by the commutator at each half revolution.

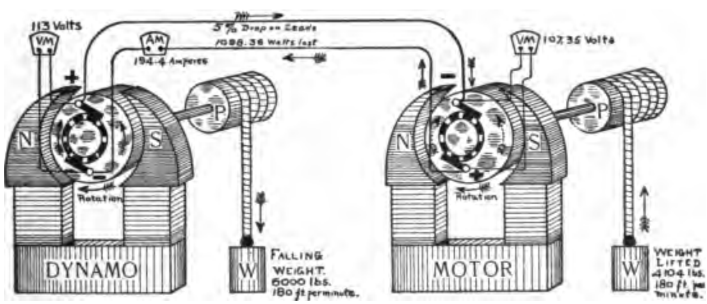
Exp. 99: Find the polarity of the field magnets with a compass, also the polarity of the supply line, and note whether the direction of rotation is according to the left-hand rule, page 278.

Exp. 100: Reverse the current at the motor terminals and the direction of rotation is the same as before. Why? Now reverse the direction of rotation, ¶ 267.

Exp. 101: Connect the motor armature in series with the two field

coils in parallel, so that the poles have the proper polarity, **N** and **S**. It is now a series motor. (a) Apply the left-hand rule, page 278, for the direction of rotation of the armature. (b) Reverse the direction of rotation, as in ¶ 267.

359. Position of the Brushes on a Motor.—The reaction of the armature current upon the field of a motor distorts it just as in a generator, ¶ 337. The lines of force are, however, now crowded together under the opposite pole tips to those illustrated in Fig. 349. The neutral line, or plane will, therefore, advance backward against the direction of rotation of the motor, and it is at this position commutation in a motor should take place. The brushes are set in the same manner as given for a dynamo in ¶ 339, but are *rocked backward against the direction of rotation* till the neutral point or non-sparking position is found. The angle of advance against the direction of rotation will increase as the current taken by the



H. P. driving dynamo = 32.7.	**Watts intake by motors, 20868.84 watts.**
Efficiency of dynamo, 90%.	**Efficiency of motor, 80%.**
Useful watts generated = 21967.2 (29.4 H. P.)	**Useful power developed by motor, 22.3 H. P.**

General efficiency of the entire transmission system, 68%.

Fig. 374.—Electrical Power Transmission.

motor increases, or as the work it is required to perform increases, and decrease as the load is removed. The conditions and remedies for the sparking at the brushes of a motor are the same as those given in ¶ 340.

360. Counter Electromotive Force of a Motor.—The armature wires of a motor, rotating in its own magnetic field, cut the lines of force just as if it were being driven as a dynamo, and consequently there is an induced E. M. F. in them. By applying the right and left-hand rules to the single coil in Fig. 373, it will be seen that if it is rotated clockwise, the di-

rection of the induced E. M. F. will tend to send a current around the coil from A to B, to C, to D, while when supplied with current as a motor, to rotate in the same direction, the applied pressure will oppose the induced pressure and cause a current to flow from D to C, to B, to A. This induced motor pressure is called the Counter Electromotive Force (abbreviated C. E. M. F.) and is always in such a direction as to oppose the direction of the pressure applied to the motor terminals, or to that of the supply mains. The dotted arrows, in Fig. 373, indicate the direction of the counter E. M. F. and the solid arrows, that of the applied E. M. F. as found by the right and left-hand rules. This counter E. M. F. is a very important property possessed by the motor, as will be shown later on. A motor, without load, will run at such a speed that its counter E. M. F. will very nearly equal the applied pressure.

The counter E. M. F. of a motor running at any speed will be the same as when it is run as a generator at this speed, provided the field strength is the same in both cases, hence to find the counter E. M. F. of a motor at any speed: run it as a generator at this speed and measure the induced E. M. F. by a voltmeter. The counter E. M. F. may also be observed by connecting a lamp across the terminals of a shunt motor, running without much load, and opening the main supply circuit when the lamp will still be illuminated and gradually become dim as the speed of the motor decreases. A voltmeter connected across the motor terminals will also indicate, by the direction of the needle's deflection, that the counter E. M. F. is opposed to that of the line E. M. F. when the supply switch is opened.

To Find the Current Flowing Through the Armature of a Motor:

Subtract the counter E. M. F. from the applied E. M. F. and divide this result by the armature resistance. Ohm's Law for a motor, then, is as follows:

Let $\mathbf{E}$ = E. M. F. applied at motor brushes;
$\mathcal{E}$ = counter E. M. F. developed by motor;
$\mathbf{I}$ = current through motor armature;
$\mathbf{r}$ = internal resistance of motor armature.

$$\text{Then, } \mathbf{I} = \frac{\mathbf{E} - \mathcal{E}}{\mathbf{r}} \quad \ldots\ldots\ldots\ldots \quad (103).$$

$$\text{Also by transposition, } \mathcal{E} = \mathbf{E} - (\mathbf{I} \times \mathbf{r}) \quad \ldots\ldots \quad (104).$$

The counter E. M. F. can never equal the E. M. F., but is always less by an amount equal to the drop in the motor armature ($I \times r$). The difference between a dynamo and motor is as follows:

Dynamo.	**Motor.**
THE MECHANICAL DRIVING FORCE IS EQUAL AND OPPOSITE TO THE COUNTER ELECTRODYNAMIC FORCE.	THE ELECTRODYNAMIC DRIVING FORCE IS EQUAL AND OPPOSITE TO THE MECHANICAL FORCE OF THE DRIVEN MACHINERY.
THE E. M. F. IS GREATER THAN THE PRESSURE AT THE TERMINALS.	THE COUNTER E. M. F. IS LESS THAN THE PRESSURE AT THE TERMINALS.

TO FIND THE COUNTER E. M. F. OF A MOTOR:

Multiply the resistance of the armature by the current flowing through it and subtract this product from the E. M. F. applied to the motor brushes, Formula (104).

The counter E. M. F. of a motor depends upon the same factors as those governing the induced E. M. F. in a dynamo, and is directly proportional to,

(*a*) *The number of lines of force cut,*
(*b*) *The number of conductors upon the armature,*
(*c*) *The speed at which the lines of force are cut.*

TO FIND THE MECHANICAL POWER DEVELOPED BY A MOTOR:

Multiply the counter E. M. F. by the current through the armature.

$$W = \mathcal{E} \times I \quad \ldots\ldots\ldots\ldots \quad (105).$$

The mechanical power developed includes that required for mechanical friction losses and the power which is expended in eddy currents and hysteresis.

Prob. 127: A small motor is connected to a 110-volt circuit; the counter E. M. F. at a particular speed is 100 volts; the resistance of the armature is 2 ohms. What current is being supplied to the motor?

By Formula (103) $I = \frac{E - \mathcal{E}}{r} = \frac{110 - 100}{2} = 5$ amperes.

$E = 110$ volts, $\mathcal{E} = 100$ volts, $r = 2$ ohms.

Prob. 128: The armature resistance of a shunt wound motor is .5 ohm, and at a certain load 10 amperes flow through it; the drop across the motor brushes is 110 volts. What is the counter E. M. F.?

By Formula (104) $\mathcal{E} = E - (I \times r) = 110 - (10 \times .5) = 105$ **volts**.

$E = 110$ volts, $I = 10$ amperes, $r = .5$ ohm.

Prob. 129: What current would the motor referred to in Prob. 127 receive if it had no counter E. M. F.?

By Formula (28) $I = \frac{E}{R} = \frac{110}{2} = 55$ amperes.

$E = 110$ volts, $R = 2$ ohms.

Prob. 130: (a) What power is developed by the motor in Prob. 127? (b) What power is supplied to the motor? (c) What is the commercial efficiency of the motor (friction losses being neglected)?

By Formula (105) $W = \mathcal{E} \times I = 100 \times 5 = 500$ watts (a).

By Formula (62) $W = E \times I = 110 \times 5 = 550$ watts (b).

By Formula (84) Com. Eff. $= \frac{W}{W + w} = \frac{500}{550} = .90 = 90\%$ (c).

There is no counter E. M. F. induced in a motor armature until it begins to revolve, so that the current flowing through it, when stationary, is equal to $E \div R$, as in Prob. 129. When the armature begins to rotate, the current through it gradually diminishes, since the counter E. M. F. rises with the speed. It requires more energy to start a motor than to maintain it at any particular speed, ¶ 210, so that the counter E. M. F. automatically acts like resistance in a circuit, and decreases the current as the speed increases.

Fig. 375.—Motor Windings Protected by Cast Iron Housing.

The great advantage, then, of counter E. M. F, in a motor is that it regulates the current without absorbing the electrical energy, as in a rheostat, where the extra energy is dissipated as heat; motors can thus be run very economically. The automatic regulation of the current, as the motor attains its normal speed, is shown in the following experiment:

Exp. 102: An ammeter is connected in series with the armature of a small motor and the current noted for several speeds read from an automatic speed indicator (tachometer) as follows:

Table XXII.—Motor Test.

Speed—Revolutions per minute.	Amperes.	Speed—Revolutions per minute.	Amperes.
0	20.0	1600	7.8
500	16.2	1800	6.1
1000	12 2	1950	5.1

At the maximum speed the motor in the above test receives 5.1 amperes, or about one-fourth of the current which would flow through it at rest. If some machinery be now connected to the motor pulley by a belt, the motor will slow down somewhat, thus decreasing the counter E. M. F. and permitting more current to flow through the armature to perform the extra work. When the load is removed the motor increases in speed, thus increasing the counter E. M. F. and decreasing the current taken from the line. There is thus a continual automatic adjustment between the current supplied to a motor and the work it has to perform, or *the electrical power taken from the supply mains by a motor is directly proportional to the mechanical power it is required to develop at its pulley.* This drop in speed of a shunt motor, running fully loaded, may be 5 per cent less than the speed the motor attains when running free.

361. Normal Speed of a Motor.—Suppose a shunt dynamo maintains a P. D. of 110 volts at its brushes when driven at a speed of 1800 revolutions, and that it is now run as a motor, and 110 volts maintained across the brushes. The field strength will be the same as when it was run as a generator, but the speed at which the motor will run will be less than 1800 revolutions, because at this speed the counter E. M. F. would be equal to the applied E. M. F., and this would be impossible, since the motor would then receive no current from the line. The counter E. M. F. equals the applied E. M. F. minus the drop in the armature, Formula (104).

Suppose the above motor attains a speed of 1600 revolutions. When run as a generator, the induced E. M. F. per revolution will be $\frac{110}{1800} = .061$ volt per revolution. At 1600 revolutions the counter E. M. F. equals $1600 \times .061 = 97.6$ volts. The drop in the armature is thus the difference between the applied pressure and the counter E. M. F., or $110 - 97.6 = 12.4$ volts. If the resistance of the motor armature is .2 ohm, then the current the armature receives when running at 1600 revolutions, is $12.4 \div .2 = 62$ amperes, Formula (28). The watts lost in the motor armature

will be, Formula (62), $12.4 \times 62 = 768.8$ watts; the watts applied to the armature, Formula (62), $110 \times 62 = 6820$ watts (9.1 H. P.), and the useful power* developed by the motor will be equal to the product of the counter E. M. F. and the armature current, Formula (105), or $97.6 \times 62 = 6051.2$ watts (8.1 H. P.). Suppose the motor fields receive 3 amperes, then the energy from the line expended in the fields $= 3 \times 110 = 330$ watts; or total energy supplied to the motor $= 6820 + 330 = 7150$ watts (9.5 H. P.) *intake* and motor *output* $= 6051.2$ watts (8.1 H. P.). The commercial efficiency of the motor is from Formula (84) and ¶ 369.

$$\frac{\text{Output}}{\text{Intake}} = \frac{8.1}{9.5} = .85 = 85\ \%.$$

The speed which any motor attains is such that the sum of the counter E. M. F. developed and the drop in the armature is exactly equal to the applied E. M. F. This is expressed by the following formula derived by transposition from Formula (104):

$$\text{Counter E. M. F.} + (I \times r) = \text{applied E. M. F.},$$
$$\text{or } \mathcal{E} + (I \times r) = E \quad . \quad . \quad . \quad . \quad . \quad (106).$$

The drop in the armature of a motor is a small percentage of the applied pressure, about 2 per cent of the terminal pressure in a 500-K. W. motor and about 5 per cent in a 1-K. W. motor, so that the counter E. M. F. nearly equals the applied E. M. F. Since the power driving a motor equals the applied pressure times the current, most of which is usefully expended in mechanical output, the counter E. M. F. is an essential and valuable feature of the motor, rather than a detriment to its operation.

362. Mechanical Work Performed by a Motor-Torque.—The mechanical work performed by a motor depends upon two factors, the speed and the torque, and is equal to the product of these factors, ¶ 213. The term "torque" is applied to the twisting force which is produced in the armature when a current is sent through it, and represents the effort made to cause rotation. This effort is made up of two components; first, the pull, measured in pounds, and second, the length of arm at which this pull acts. The most common method of testing the mechanical output of a

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* Neglecting friction losses, etc.

motor is with the Prony brake, Fig. 376. The brake consists of a lever arm of wood hollowed out to fit pulley and clamped to it by bolts passing through a wooden block on opposite side of pulley, bolts being fitted with wing nuts, by means of which the pressure on surface of pulley can be adjusted, thus altering the force due to friction and the pull at the end of the lever arm. By measuring this pull, the speed of rotation, and the length of the lever arm, the power developed can be readily calculated.

Method.—The principle of the brake is quite simple, for it is evident from Fig. 376, that due to the friction of the clamp on motor pulley there is a tendency to make the lever arm pull or rotate. The tendency to pull or rotate is measured by a spring balance or by means of a platform scale, the lever arm resting on a V block on platform of scales. Work is equal to the product of force and the distance, (W = F × S ¶ 213). The distance r, (Fig. 376), from the center of the shaft to the point of application of the force resisting the tendency of the lever to rotate, is ascertained by careful measurement. In one revolution of the pulley, the brake arm if allowed to rotate with it would describe a circle having a radius r (length of arm, Fig. 376), the distance then through which the point of application of the force would travel would equal $2\pi r$, † and if the number of revolutions is S, the power, in foot-pounds per minute, is Power $= 2\pi r S F$, where F equals the force of pull in pounds. To reduce this to horse power, it is necessary to divide by 33,000, since one mechanical horse power equals 33,000 ft. lbs. of work per minute, page 211, or,

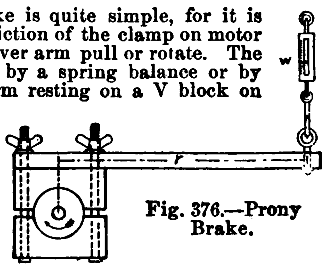

Fig. 376.—Prony Brake.

$$\text{H. P.} = \frac{2\pi r S F}{33{,}000}$$

363. Output and Rating of Motors.—The capacity of a motor to perform useful work is limited by the same conditions as those governing the capacity of a generator, ¶ 341. Motors are commercially rated according to the amount of power they will maintain at full load, at their pulleys, within the limit of permissible heating. For example, a 10-K. W. 110-volt motor will, when supplied with 110 volts at its terminals, develop 10 K. W. or 13.4 horse power at the pulley. A dynamo will have less capacity when driven as a motor than when driven as a generator, since in the latter case the driving engine furnishes the additional power to overcome the friction and internal losses, while a motor must develop this extra power. For example, suppose it requires 17 K. W. from an engine to drive a dynamo with 15 K. W.

† The Greek letter π (pi) represents the relation between the diameter of a circle and its circumference, and is equal to 3.1416. Circumference of a circle $= \pi \times d$, where d = the diameter.

output, wound to deliver 100 amperes to the external circuit at full load, and this machine is to be used as a motor. The permissible intake, within the heating limit, will be 15 K. W. at 100 amperes, and since 2 K. W. were previously required for friction losses, eddy currents, etc., only about 13 K. W. output will be available at the motor pulley. A motor will thus be somewhat larger than a generator of the same capacity.

364. Motor Speed and Torque.—There are three different classes of work to be performed by motors, requiring as many different conditions of motor speed and torque, as well as a particular type of motor for the work to be performed.

First. When a motor is required to drive a crane, a hoist, or an elevator, it must run with constant torque at a variable speed, since the load is constant and is to be moved at varying rates of speed.

Second. A motor used to drive a line shaft in a machine shop must run at constant speed, regardless of the number of machines in operation, or the work being performed by them, which illustrates the case of variable torque and a constant speed.

Third. Both of the above conditions are encountered in street railway work where the motor is required to develop a variable torque and variable speed; for example, in starting a car the torque required is a maximum and the speed a minimum; when the car gains some headway the torque diminishes and the speed increases.

Thus, according to the character of the work to be performed, motors must develop either,

(a) *Constant torque at variable speed,*
(b) *Variable torque at constant speed,*
(c) *Variable torque at variable speed.*

A series wound motor operated from constant potential mains is generally used for cases (a) and (c), while a shunt motor operated from a constant potential circuit fulfils the conditions required in case (b). Ordinarily, direct current motors are built for 110, 220 or 500-volt constant potential circuits; the advantage of the higher potential motor being, that for a given amount of power to be developed, a smaller size lead wire is required; for example, the size of wire required to

transmit 10 K. W. at 500 volts must be sufficient to carry 20 amperes, Formula (63); at 200 volts, 50 amperes; and at 100 volts, 100 amperes. The greater the number of field poles the lower will be the motor speed to develop any given power.

365. Methods of Motor Speed Regulation.—The following two methods are usually employed for regulating the speed of motors connected to constant potential circuits:

(*1*) *By inserting resistance in the armature circuit of a shunt wound motor.*

(*2*) *By varying the field strength of series motors by switching sections of the field coils in or out of circuit.*

First method.—This method is depicted in the upper half of Fig. 378. When the switch, A, is closed the motor fields are first excited and by moving the arm, S, of the rheostat to point 1, the armature circuit is completed with the extra resistance in series with it. Suppose a shunt motor to be operated from a 100-volt circuit, requiring 50 amperes to produce the required torque for a particular load, and that the resistance of the armature and extra resistance in series with it, 1 to 5, Fig. 378, is 2 ohms. By Formula (29) the drop on this resistance with a current of 50 amperes through it is 100 volts, so that the motor armature is not required to develop any counter E. M. F., or it remains at rest, supporting the weight from its pulley but not moving it. Reduce the resistance in the armature circuit to, say 1.5 ohms, by moving S to point 3; the motor armature now turns and runs at such a speed that the counter E. M. F. will be equal to the value of drop on the resistance so cut out (or $50 \times .5 = 25$ volts) and the weight is lifted at a proportionate speed. With the armature at rest 5 K. W. (100×50) were uselessly expended in heating the resistance; in the second instance a portion of this energy appeared as useful work. Continue to decrease the resistance in the armature circuit by moving arm S to the right, and the speed increases and a greater portion of the energy is available for useful work. This is not an economical method of regulating the speed of a motor, since the energy taken from the line (5 K. W.) is the same whether the motor be running at a very slow speed or at a high one. The rheostat used for series regulation of this character must be of such a capacity as to carry nearly the entire intake of the motor without injurious heating.

366. Speed Regulation of Series Motors— *Second Method.*—The method of regulating the speed of a series wound motor, by increasing or decreasing its field strength by varying the turns around the field, is illustrated in Fig. 377. The current through the motor armature will flow through all the field windings when the position of the switch arm, S, is on point 1, so that the field will then have its maximum strength and will be decreased as the arm is moved to point 2, 3, etc. *Increasing the field strength of a motor decreases its speed, while decreasing the field strength increases the speed.** This is shown by the following example. Suppose a street car to be running on a level road at such a speed that the motor develops a counter E. M. F. of 400 volts, while the applied E. M. F. is 500 volts; assume the resistance of the armature to be 1 ohm. The motor current will be:

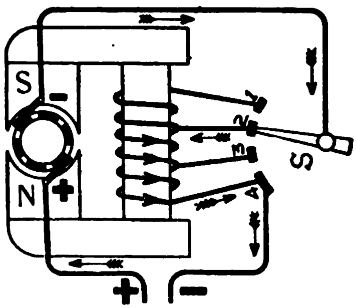

Fig. 377.—Speed Regulation of a Series Motor.

By Formula (103) $I = \frac{E - \mathcal{E}}{r} = \frac{500 - 400}{1} = 100$ amperes.

The power developed by the motor will be,

By Formula (105) $W = \mathcal{E} \times I = 400 \times 100 = 40000$ watts (53.6 H. P.).

Suppose it is desired to run the car more slowly. *Increase the field strength*, say 10 per cent, by moving switch, S, so as to insert more turns in the field circuit. The counter E. M. F. at the same speed as before would be 10 per cent higher, or 440 volts, and the current received by the motor,

By Formula (103) $I = \frac{E - \mathcal{E}}{r} = \frac{500 - 440}{1} = 60$ amperes,

or the power now developed,

By Formula (105) $\mathcal{E} \times I = 440 \times 60 = 26400$ watts (35.3 H. P.).

* In a dynamo increasing the field strength increases the E. M. F., while decreasing it decreases the E. M. F.

Since it required 53.5 horse power to maintain the first speed the car must now run more slowly when the motor develops only 35.3 H. P.

Under the conditions of maximum field strength of a motor, as with switch S on point 1, the torque will be greatest for any given current strength, and the counter E. M. F. also greatest at any given speed. The current through the armature of the motor, to perform any given work, will thus be a minimum, as well as the speed at which the motor has to run, in order to develop sufficient counter E. M. F. to permit this current to flow. If the field strength could be increased indefinitely it would then be possible to make the motor develop a very high counter E. M. F at a very low speed. With very light loads, then, to be moved at a slow rate of speed, the motor would take current from the line in proportion to the load. Suppose the load is to be moved more rapidly; decreasing the field magnetising force permits the motor to attain a higher speed to generate its necessary counter E. M. F. at the reduced field strength, with correspondingly more current taken from the line, since the rate of working at the higher speed is increased. Regulation of speed by varying the field strength is limited in range of action, since the field saturation point is soon reached; on the other hand, with too low a field strength the armature reaction upon the field produces excessive field distortion, sparking, etc.

The speed of a series motor may be nearly doubled by this method of regulation, that is, if the lowest permissible speed is 250 revolutions it may be increased to 500 revolutions. In practice this regulation is effected by commutating the field coils, from series to parallel; for example, suppose 50 amperes to flow through two sections of a field coil containing 100 turns each, the total turns are therefore 200 and the magnetising force, Formula (54), $50 \times 200 = 10000$ A. T. With the two coils in parallel and 50 amperes through the circuit the total magnetising force is now only 5000 A. T., so that the field strength is diminished. By this method the resistance of the motor circuit is also lessened, so that, to some extent, the method includes the rheostat control described in ¶ 365, but is far more economical for the reasons given above. A rheostat inserted in the field circuit of a shunt motor will regulate the speed, within limits, in the same manner.

367. Series Motors for Railway Work.—Series motors

are used for railway work, because they best fulfill all the requirements, such as powerful torque at starting, variable speed and economical speed regulation for varying loads. When two motors are used their armatures and field coils are connected in series with each other and an extra resistance, which prevents too great a rush of current from the mains before the car starts. As the car gains headway a barrel cylinder switch termed a *series-parallel controller* * gradually cuts the extra resistance out of circuit and commutates the field windings from series connection to parallel, and, finally, connects each motor directly across the mains, or between the overhead trolley line and the track, which is used as the ground return; one terminal of the station generator being connected to the trolley line and the other to the track. The fields of series railway motors are designed so as to become saturated with less than the total current required by the motor at full load. When the resistance of the field circuit is diminished a higher P. D. is applied at the motor brushes, causing a higher speed to be maintained by reason of the additional armature current. This current also flows around the field, but being saturated there is no tendency to decrease the speed, as would be the case if the field were below saturation point. In this manner different E. M. F.'s may be applied to the armature without affecting the field strength. Complete connections for two standard series motors, as used on the ordinary trolley car, are given in Plate II.

368. Operating Motors.—The resistance of the armature of motors is very low; for example, the armature of a 220-volt 10-K. W. shunt motor has a resistance of about .2 ohm. If this motor were directly connected to the supply mains, as by closing the switch A, Fig. 378, a much greater current than that required for full load would flow through it before any counter E. M. F. could be developed, resulting in damage to the windings; the low resistance would practically short-circuit the mains, causing an excessive drop of voltage. See Prob. 129. For this reason a rheostat, called a *starting box*, Fig. 378, is always inserted in the armature circuit of a shunt motor to prevent this extra rush of current before the motor attains its speed. The value of this extra resistance should be such that, when added to the armature resistance,

it would permit only the full load current taken by the motor to flow from the mains. As the motor attains some speed, and counter E. M. F., this resistance is gradually cut out by moving arm, S, from post 1, to 2, to 3, etc., until at point 5 the line is directly connected across the motor. For example, to start the shunt motor close switch, A, when the motor fields will be excited; move the arm, S, of the starting box to point 1, when the armature circuit will be completed in series with the extra resistance; cut out the extra resistance as the motor attains speed by gradually moving S to point 5. To stop the motor, open the main switch, A, and then place the arm of the starting box on the off position, so that the motor will be ready for re-starting.

In an *automatic motor starting box*, such as that depicted in Fig. 123, the arm, S, carries a small piece of iron, P, Fig. 378, and turns against the action of a spring; an electromagnet, M, in series with the shunt field is mounted on the

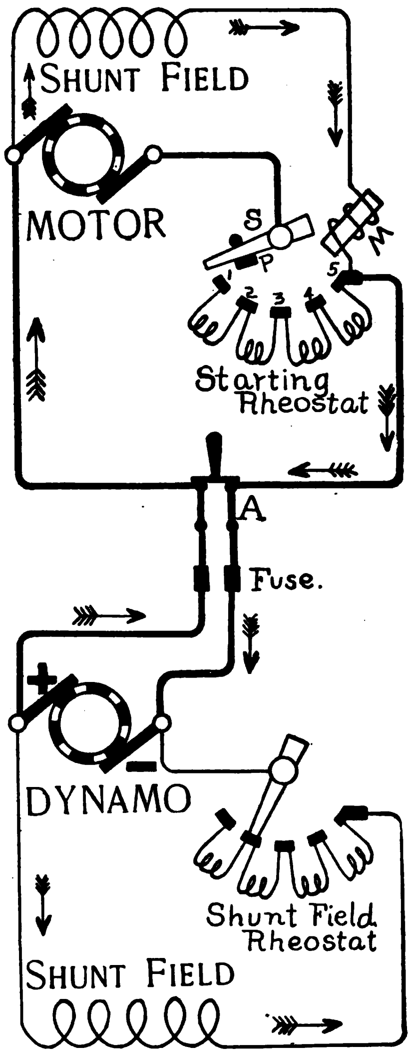

Fig. 378.—Connections of a Shunt Motor to a Dynamo Circuit.

box, and when arm, S, rests on point 5 it is held there by the electromagnet against the action of the spring. The advantage of this arrangement is, that if for any reason the main power supply circuit should be interrupted, the starting box arm will automatically open the circuit and shut the motor down, instead of permitting the motor armature to cause a short-circuit across the mains when the power is again turned on.

Shunt motors should be started with the driven load disconnected, it being switched on to the motor when the maximum speed is attained. *In starting a shunt motor always be sure that the fields are first excited* (test their attractive power with a penknife), since without the field excitation the armature could not generate a counter E. M. F., but would take an excessive current from the line.

The resistance and the self-induction of the armature and fields of a series motor tend to check the sudden rush of current through it, so that in some cases this motor might be directly connected to the mains without injurious effects. Usually, however, some extra resistance is connected in the motor circuit, and gradually cut out as before.

369. Efficiency of a Motor.—The commercial efficiency of a motor, as in the case of the dynamo, ¶ 344, is the ratio of the output to the intake. The energy furnished to the motor is readily measured, and from this must be subtracted the losses in the motor to obtain the available energy. These losses are divided into two classes: the I^2R losses in the armature and fields, and the mechanical losses, which include friction, eddy currents and hysteresis.

Prob. 131: The pressure applied to a motor having a resistance of 2 ohms is 110 volts. What power is developed by the motor when the counter E. M. F. is (a) 80 volts? (b) 55 volts? (c) 40 volts?

By Formula (103) $I = \frac{E - \mathcal{E}}{r} = \frac{110 - 80}{2} = 15$ amperes.

By Formula (105) $W = \mathcal{E} \times I = 80 \times 15 = 1200$ watts (a);

$$\text{also } \frac{110 - 55}{2} = 27.5 \text{ amperes,}$$

$$\text{and } 27.5 \times 55 = 1512.5 \text{ watts (b);}$$

$$\text{also } \frac{110 - 40}{2} = \frac{70}{2} = 35 \text{ amperes,}$$

$$\text{and } 35 \times 40 = 1400 \text{ watts (c).}$$

From this problem it will be noted that the power developed by a motor increases as the counter E. M. F. decreases, until the counter E. M. F. equals one-half the applied E. M. F., after which point the motor develops less power as the counter E. M. F. decreases. The maximum work is done when the counter E. M. F. is just equal to one-half the applied E. M. F.

370. Electric Traction.—The chief factor in stationary motors is the work the motor can perform without becoming too warm or decreasing too much in speed, while in street car motors the most prominent factor is the torque, or the tractive force, the motor is capable of developing at different speeds with different loads.

The tractive force is the force exerted by the motor on the car in the direction of its motion.

On a level road the tractive force of a motor varies with a number of conditions, such as road bed, track, lubrication of journals, weight, etc.

The tractive force varies directly as the weight of the car and the passengers carried. For average conditions about 25 pounds tractive force (torque) are required for each ton propelled by the motor on a level road, with a speed of from 6 to 10 miles per hour. For example, to propel a car weighing 6 tons, with passengers aboard weighing 3 tons, will require a tractive effort on a level of 9 × 25 or 225 pounds.

TO FIND THE WATTS REQUIRED TO PROPEL A STREET CAR ON A LEVEL ROAD AT A CERTAIN SPEED;

Multiply the tractive force by the speed in feet per minute to obtain the foot-pounds of work performed per minute, and divide by 33,000 to obtain the horse power; multiply the H. P. by 746 to obtain the watts output of the motor, and divide this product by the efficiency of the motor to obtain the watts required by the motor from the line, Formula (107).

Let W = watts required by the motor on level road;
F = tractive force = 25 lbs. per ton;
% M = efficiency of the motor;
T = weight of the car and passengers, *in tons;*
S = speed of car, in feet, per minute.

Then, $$W = \frac{\dfrac{T \times F \times S}{33000} \times 746}{\% M} \qquad (107.)$$

Prob. 132: A street car weighs 7 tons, and the passengers aboard, 3 tons; the tractive force is 25 pounds per ton; efficiency of motor, 75%. How many watts are supplied to the motors when the car is propelled at a speed of 10 miles an hour on a level road?

Total weight $= 7 + 3 = 10$ tons $\times 25 = 250$ pounds tractive force.

Feet traveled per minute $= \dfrac{10 \times 5280}{60} = 880.$

Foot-pounds of work per minute $= 880 \times 250 = 220000.$

Horse power developed by motor $= \dfrac{220000}{33000} = 6.6.$

Watts developed by motors $= 6.6 \times 746 = 4923.6.$

Watts delivered to motors $= \dfrac{4923.6}{.75} = 6564.8.$

Or by Formula (107) $W = \dfrac{\dfrac{T \times F \times S}{33000} \times 746}{\% \text{ M}} =$

$$\dfrac{\dfrac{10 \times 25 \times 880}{33000} \times 746}{.75} = 6564.8 \text{ watts.}$$

When the car ascends a grade a certain amount of *additional energy is required to propel it*, and this is represented by the amount of energy required to raise the car through the distance it travels vertically.

TO FIND THE ADDITIONAL POWER REQUIRED TO ENABLE A CAR TO CLIMB A GRADE:

Multiply the per cent of the grade by the speed of the car in feet per minute, to obtain the vertical distance traveled per minute; multiply this product by the weight of the car and the passengers, expressed in pounds, to obtain the total foot-pounds of work performed; divide this product by 33,000 to obtain the horse power, and multiply the quotient by 746 to obtain the watts output of the motor; divide this result by the efficiency of the motor to obtain the watts taken from the line, Formula (108).*

Let $\%G$ = the per cent of grade;
W_1 = additional watts required to ascend the grade;
T_1 = weight of car and passengers, *in pounds.*

$$\text{Then, } W_1 = \dfrac{\dfrac{\% G \times S \times T_1}{33000} \times 746}{\% \text{ M}} \quad \ldots\ldots\ldots\ldots \quad (108).$$

* A 10 per cent grade means a vertical rise of 10 feet in every hundred feet traveled, a 7 per cent grade, 7 feet, etc.

TO FIND THE TOTAL WATTS REQUIRED FOR A CAR TO ASCEND A GRADE :

Add the watts required for a level road to the additional watts required for the grade, Formula (109).

$$\text{Total watts required} = W + W_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (109).$$

Prob. 133: How many watts must be supplied to the motors in Prob. 132, in order that the car will ascend a 10 % grade?

Vertical rise in feet per minute $= 880 \times .10 = 88.$
Total weight of car, in pounds $= 10 \times 2000 = 20000.$
Foot-pounds of work per minute $= 20000 \times 88 = 1,760,000.$

$$\text{Horse-power} = \frac{1760000}{33000} = 53.3$$

Watts output of motors $= 53.3 \times 746 = 39761.$

Watts required by motors $= \frac{39761}{.75} = 53015,$ or by Formula (108)

$$W_1 = \frac{\frac{\% G \times S \times T_1}{33000} \times 746.}{\% M} = \frac{\frac{.10 \times 880 \times 20000}{33000} \times 746.}{.75} = 53015.$$

By Formula (109) total watts required $= W + W_1 = 6564.8 + 53015 = 59579$ watts or 59.5 K. W.

QUESTIONS.

1. How does a motor differ from a dynamo?
2. What is the difference between a shunt and series motor?
3. A series dynamo rotates clockwise. What will be the direction of rotation when it is used as a motor?
4. A shunt dynamo runs in a counter clockwise direction. How will it run when driven as a motor?
5. What is necessary in order to properly run the shunt dynamo in question 4 as a shunt motor and in a clockwise direction?
6. Since the counter E. M. F. of a motor permits less current to flow through it than if it did not exist, and the turning effort of a motor depends on the current through the armature, of what advantage then is the counter E. M. F.?
7. State two methods by which you can prove a motor to possess counter E. M. F.
8. How would you measure the counter E. M. F. of a motor?
9. Upon what factors does the counter E. M. F. depend?
10. A shunt motor is called a *constant speed* motor; how is it possible then for the motor to take current from the line in proportion to the power it develops, since if it always runs at constant speed the counter E. M. F. would be constant, and therefore the current constant?
11. Why is it impossible for the counter E. M. F. of a motor to attain a value equal to the applied E. M. F.?
12. A 15-K. W. shunt motor is to be used as a dynamo. Will its output be more or less than 15 K. W.? Why?

13. What factors determine the mechanical work which can be performed by a motor?

14. What is meant by motor torque?

15. What is the difference between motor speed and motor torque?

16. State the conditions of torque and speed that motors are required to develop in commercial work, and the kind of motor adapted to each case.

17. Explain two methods of motor speed regulation, stating the advantage or disadvantage of each method. Illustrate your answer by sketches.

PROBLEMS.

1. A shunt motor having an armature resistance of 2 ohms and a field resistance of 125 ohms is connected to a 250-volt main and develops a counter E. M. F. of 220 volts. What current is taken from the line? *Ans.* 17 amperes.

2. What mechanical power is developed by the motor in problem 1? *Ans.* 4.4 H. P.

3. If there are 500 watts lost in mechanical friction, hysteresis and eddy currents in the motor in problem 1, what useful power can the motor develop? *Ans.* 3.7 H. P.

4. What is the commercial efficiency of the motor mentioned in the above problem? *Ans.* 65 %.

5. Fifty amperes flow through a motor armature havng a resistance of 3 ohms when it is connected to a 250 volt supply circuit. What counter E. M. F. is developed? *Ans.* 100 volts.

6. What mechanical power is developed by the motor armature in problem 5? *Ans.* 6.7 H. P.

7. A shunt motor runs at 1400 revolutions; when connected to a 220-volt circuit and driven as a dynamo it generates 220 volts P. D. at a speed of 1600 revolutions. What is the counter E. M. F. when the machine is used as a motor? *Ans.* 192.5 volts.

8. The resistance of the armature in problem 7 is 2 ohms. What current flows through it when it is run as a motor? *Ans.* 19 amperes.

9. The fields of the motor in problems 7 and 8 receive 5 amperes; if 458 watts are required for mechanical losses what is the commercial efficiency? *Ans.* 56%.

10. In making a brake test on a motor, the lever arm of brake is 3 feet, motor running at 1150 revolutions per minute when exerting a pull of 25 pounds. (*a*) What is the motor torque? (*b*) What H. P. is developed? *Ans.* (*a*) 541811 ft. lbs. (*b*) 16.4 H. P.

11. The counter E. M. F. of a motor is 230 volts; the current through the armature 25 amperes, its resistance 4 ohms. What is the applied E. M. F.? *Ans.* 330 volts.

12. A street car is propelled by two motors, driven from a battery of accumulators weighing 2½ tons, which is placed beneath the car seats; the motors weigh 1 ton, the car 4 tons, the passengers aboard 2½ tons, the efficiency of the motor is 80%. What power is supplied to the motors from the battery when the car is running on a level road at 8 miles per hour? *Ans.* 4942 watts.

13. The street car, in problem 12, is required to ascend an 8 % grade at the reduced speed of 4 miles per hour. What is now the total power taken from the cells? *Ans.* 20794 watts.

LESSON XXX.

ELECTRIC LIGHTING

The Electric Arc—Crater of Arc—Characteristics of the Electric Arc—Rating of Arc Lamps—Arc Lamp Carbons—Arc Lamp Regulation—Commercial Arc Lamps—Mercury Vapor Lamp and Nernst Lamp—Incandescent Lamps—Lamp Filaments—The Tungsten Filament Lamp—Commercial Rating of Incandescent Lamps—Life and Efficiency of a Lamp—Incandescent Lamp Circuits—Potential Distribution in Multiple Lamp Circuits—Loss on Transmission Lines—Incandescent Wiring Calculations—Three Wire System—Motor Wiring Calculations—Questions and Problems.

371. The Electric Arc.—When a current of from 6 to 10 amperes, under a pressure of about 45 volts, is passed through two carbon rods, with their ends first in contact and afterward gradually separated a short distance, as one-eighth inch, a brilliant arc of flame called the *electric arc,* is established between them. This arc is composed of carbon vapor that is, the high temperature caused by the passage of the current through the resistance of the contact surfaces causes the carbon to practically boil and the vapor thus arising, being a much better conductor than the air, conducts the current across the gap from one carbon tip to the other. This volatilization occurs chiefly at the end of the positive carbon terminal where the current enters the arc, and this point is also the seat of the highest temperature and maximum light-emitting power. As the arc is maintained across the gap, disintegration of the carbon takes place, the carbons waste away, and a cup-shaped depression, termed the *crater,* is formed in the *positive carbon,* while the tip of the negative carbon has a conical form, Fig. 379. The negative carbon being at a lower temperature than the positive, the vapor of the boiling carbon condenses upon its surface as pure graphite. Both carbons waste away, but the consumption of the positive carbon is about twice as rapid as that of the negative, since it is this carbon from which most of the vapor comes and

part of which is re-deposited as graphite on the negative cone-tipped carbon.

372. The Crater of the Arc.—The light emitted by any heated body increases with its temperature. The temperature of the carbon in the crater, when in a state of ebullition, is about 3500° C., this being the hottest portion of the arc, and consequently the point from which the most light is emitted. The intense heat in the crater will be realized when the melting point of platinum is considered, which is 1775° C. About 12 per cent of the energy supplied to an electric arc appears as light, the balance being represented by the heat evolved. About 85 per cent of the light emitted from an arc lamp is reflected from the crater, so that arc lamps are usually arranged with the carbons vertical and with the positive carbon above the negative, so that the light is reflected downward, the maximum illumination being in a zone surrounding the lamp at an angle of about 40° to the horizontal, and indicated by the arrows in Fig. 379.

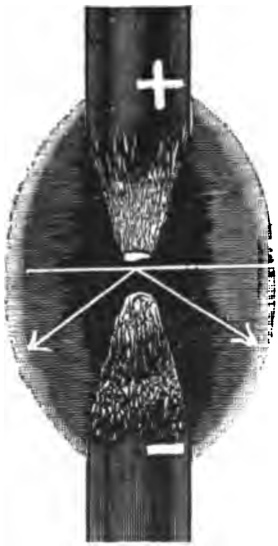

Fig. 379.—The Electric Arc. The white area in the positive carbon represents the crater; the arrows indicate the direction of the maximum zone of illumination.

373. Characteristics of the Electric Arc.—When the arc is "struck" by bringing the carbon electrodes together, and then, separating them for a short distance, the arc possesses peculiar characteristics depending upon the length of the gap between the ends of the carbons. When this distance is too small the arc emits a peculiar hissing noise, and is called a *hissing arc.* It is caused by a too rapid volatilization of the carbon, due to the excessive current that would flow through the lamp with a short gap between the carbons. *Spluttering sounds* produced by the arc are due to impurities in the carbon, or loose-grained carbons. By adjusting the distance between the carbons, a point will be found where the arc burns quietly and

steady, and is then termed a *normal* or *silent arc;* if this distance be exceeded, the arc *flames.* Impure carbons, or carbons not properly baked will produce a *flaming arc,* which is accompanied by a loss of light and a rapid increase in carbon consumption.

In commercial lamps automatic regulation, ¶ 376, is employed to feed the carbons as they are consumed, and thereby maintain the proper length of arc required for *normal* or *silent* burning. With a constant current, the resistance of the arc varies directly as its length; it will decrease as the area of conducting vapor is increased, and also as the temperature increases.

374. Rating of Arc Lamps.—At one time the ordinary commercial arc lamps were rated in candle-power, 1200 C. P. and 2000 C. P. lamps being standard. This rating was only nominal, as a 2000 C. P. lamp was one in which 450 watts was consumed, and 1200 C. P. a 300-watt lamp. The actual candle-power of such lamps is much smaller than indicated by the rating. The 450-watt lamp giving from 600 to 700 C. P. in one direction in the zone of maximum illumination, Fig. 379. At the present time arc lamps are not rated in candle-power but in current, volts, and watts consumed. The voltage used in practice for direct current *open* arc lights varies from 45 to 50 volts at the arc, with a current of from 6 to 10 amperes, a common value being 9.6 amperes and 47 volts at the arc. The voltage at the terminals of an arc lamp is greater than that across the arc, since there is some drop on the solenoids or magnets used in the lamp's regulation, ¶ 376.

375. Arc Lamp Carbons.—There are two classes of carbons generally used in arc lamps, solid and cored; they are composed of coke, tar, or the graphite deposited in the inside of retorts used for manufacturing illuminating gas. With solid carbons the crater travels around the ends of the carbons, the current always tending to take the path of least resistance; with *cored* carbons, which are solid except for an inner core of softer carbon, the travel of the crater is reduced and the distribution of light more steady. The effect of the core is to confine the current to the center of the rod, and consequently the arc, due to the core having a higher conductivity than the surrounding material. With cored carbons the voltage across the arc is reduced.

Carbon rods are often copper-plated to within a short distance of the pointed ends, the object being to reduce the contact resistance of the carbon, the carbons also lasting longer when so plated.

Fig. 380.—Single Carbon Automatic Feed Arc Lamp.

The arc is exposed to the air and the lamp trimmed nightly.

The diameter of the carbons is proportional to the current, for a 6.8 ampere open arc lamp $\frac{7}{16}$ inch, and $\frac{5}{8}$ inch for a 9.6 ampere lamp; the length being 12 inches for the positive carbon, and 7 inches for the negative, and burning about 10 hours.

In an alternating current arc the crater alternates from one carbon to the other with each reversal of current, so that both carbons are consumed equally when the rods are horizontal. When vertical, the upper carbon will be consumed about 8 per cent faster, owing to the action of the ascending currents of heated air.

376. Arc Lamp Regulation.—In order to produce and maintain the arc, the regulating devices in an arc lamp are required, first, to place the carbon in contact and then draw them apart the required distance; sceondly, this distance must be maintained as the carbons are consumed. The general principle employed in the automatic regulation of arc lamps is the pull of a spring, gravity, or both against the pull of one or more solenoids. The arrangement of solenoids gives rise to two general types of lamps for operation on a *series circuit*, the *differential* and the *shunt*. The *differential* lamp consists of a series solenoid connected in series with the two carbon rods and to the main supply line. The series solenoid is wound with a few turns of heavy wire of sufficient size to carry the total current flowing through the lamp. Another coil the shunt solenoid of a much higher resistance is connected in shunt with the arc. Both coils act upon a hinged armature which controls a clutch engaging a long rod carrying the upper carbon. The series solenoid is used to raise the upper carbon and the shunt solenoid to lower it. The action is as follows: the carbons are in contact until the current is turned on; as soon as the current is on the series coil is energized,

moving the armature in a direction to raise the positive or upper carbon a certain fixed distance "striking" the arc. As the current consumes the carbons, the length of the gap and its resistance increases, which shunts more current through the shunt coil, when at a certain instant, its attractive force for the armature overcomes that of the series coil; this action lowers the upper carbon to its former fixed distance, corresponding to the normal length of the arc.

The two coils thus work in opposition to each other, illustrating the differential principle, the length of the arc being maintained practically constant. If for any reason the clutch should fail to release the upper carbon, or the carbon break, the resistance of the gap would be increased to such an extent that an abnormal current would be shunted through the shunt coil; in series with the shunt coil is a smaller coil actuating a switch which automatically cuts the lamp out of circuit, and at the same time introduces a resistance in parallel with the shunt coil allowing the current to flow to the other lamps operated in the same series circuit. When arc lamps are provided with such automatic cut-outs, and connected in series there is no danger of interrupting the service by failure of one lamp to burn properly.

In the *shunt* lamp, a spring takes the place of the series coil and serves the same purpose. With no current in the lamp the carbons are in the position occupied when current was cut off, that is, not in contact, as the spring pulls continuously, clamping the clutch until the shunt coil is energized. When the current is turned on the carbons are fed together, when they touch the shunt coil is short circuited the spring pulling the carbons apart. As the arc lengthens the voltage across it increases until the shunt coil overpowers the spring and the clutch is loosened.

In arc lamps for use on constant potential *multiple* circuits, a solenoid in series with the carbons takes the place of the shunt coil in series lamps, its function being to release the clutch as the current is reduced below a certain value. The decrease of current is due to the increased resistance of the arc, caused by the lengthening of the arc as the carbons are consumed. When current in such a lamp

is turned on the carbons are in contact and are drawn apart by the action of the solenoid upon the mechanical device controlling the clutch that grips the upper carbon. As the carbon burns away, thus increasing the length of gap between them, and also the resistance of the circuit, less current flows. This weakens the regulating solenoid, releasing the clutch on the upper carbon, so that it falls and touches the lower carbon again; the striking of the arc taking place as at first. In order that the mechanism adjusting the carbons may not be too rapid, a device, termed a dashpot is connected with it. The dashpot consists of a graphite plunger closely fitting a metal cylinder and so arranged that the carbons may be fed together quickly, but separated slowly. In all multiple lamps a *balancing coil*, which consists of a resistance for direct current lamps and a reactance for alternating current lamps is connected in series with the arc, its object being to steady the current, the coil being used to adjust the voltage across the arc.

377. Commercial Arc Lamps.—The open arc lamp, which was formerly used exclusively for street lighting, has in recent years been replaced to a great extent by the *enclosed* arc lamp, operating in series on a *constant current* circuit. The enclosed arc lamp is used to a great extent for indoor lighting, as in stores and factories, etc., and operated in *multiple* on *constant potential* circuits. There are, therefore, *series* or constant current lamps and *multiple* or constant potential lamps; either type adapted to direct or alternating current and using the methods of regulation described in ¶ 376. Arc lamps for street lighting are usually operated in series on *constant current circuits* because the lights are distributed over a large area and the energy can be more economically supplied at a high pressure and a small current.

Suppose 100—50 volt, 10 ampere arc lamps connected in series are to be distributed over a circuit 5 miles long, a No. 6 B. & S. copper wire having a resistance of about 2 ohms per mile may be used. The resistance of the 5-mile circuit would equal 10 ohms, and carrying a current of 10 amperes the drop on the line would be 100 volts, Formula (29), and the loss in watts on the line 1000, Formula (62), or 1 K. W.

The P. D. at the generator terminals will be 5100 volts; the total energy supplied to lamps and line 51 K. W. with an efficiency of transmission of 98 per cent (50÷51). To operate the 100 lamps from

a low voltage constant potential multiple circuit the line would have to carry 1000 amperes and for the same loss on the line the weight of copper would be more than 1000 times as great as for the series circuit. See problem 91, page 234, also ¶¶ 348 and 353.

Enclosed Arc Lamp.—In this lamp a small glass globe is tightly fitted to the lower carbon, so that it passes up through the globe which is covered at its upper end, with a corrugated iron washer having a central hole slightly larger than the diameter of the carbon rod used, thus permitting it to move freely and providing a slight intake for air. When the arc is struck the available oxygen is soon exhausted and the bulb is then filled with highly heated nitrogen, carbon monoxide, and carbon dioxide. The little oxygen which enters through the top cover of bulb is very desirable, since it unites with the free carbon dust coming from the arc, forming a gas, in which the free carbon is consumed, thus preventing it from being deposited on the inside of the bulb.

Fig. 381.

Interior of Enclosed Arc Lamp showing regulating coils on the left, ballasting resistance on the right.

By excluding all but a very small amount of oxygen the consumption of the carbons is diminished and the length of the arc increased; with the increased length of arc the potential across the arc is increased to about 80 volts and the current of the average lamp reduced to about 5 amperes. The chief advantages of enclosed arcs are the saving of carbons and the diminished cost of labor for trimming. On *open* arc lamp having one set of carbons will burn from 8 to 10 hours, while an *enclosed* lamp will burn about 100 hours. Fig. 381 shows the interior of an enclosed arc lamp.

Alternating Current Arc.—In arcs fed from an alternating current there is not a continuous flame, but the arc is lighted and extinguished with each reversal of current. That the reversals may not cause the lamp to flicker, it is not practical to burn lamps on alternating current circuits of less than 60 cycles, 120 reversals per second. There is no crater, since each carbon acts as a positive at every other alternation, and the carbon consumption is

nearly the same, ¶ 375. In the open arc, using alternating current, both carbons are cored in order to obtain sufficient carbon vapor to maintain the current's path at the instant the current reverses. For this reason the current must be larger than for direct current open arcs, usually about 15 amperes, with 30 to 35 volts across the arc. The enclosed arc lamp for operation on alternating current circuits is similar to the direct current enclosed lamp except for the lamination of the magnetic parts, and the use of an adjustable reactance or choke coil, ¶ 298, in place of a resistance. Either, one or both carbons may be cored, one cored and one solid carbon gives the best results, producing the highest voltage arc that will be stable, and reducing the amount of carbon dust that would be deposited on the inside of the enclosing bulb.

FLAMING ARC LAMP.—In the standard carbon arc lamps, practically no light is given out from the arc itself, the light being produced by the incandescence of the carbon terminals. Recent improvements in arc lamps have produced a lamp in which the arc itself has been made luminous. In this lamp carbon electrodes are used having a core made up of a mixture of powdered carbon, mineral salts and a suitable binder. The presence of mineral salts in the carbon produces between the carbon terminals a vapor path conveying the particles of light producing substances. Owing to the presence of these substances in the arc, the temperature of the carbon is reduced, so that they produce very little light, the greatest illumination coming from the arc flame. Both carbons are fed point downward at an angle toward each other, thus obtaining maximum illumination without interference and shadows. The lamp requires about 45 volts at the arc and from 10 to 12 amperes. Flaming arc lamps are best suited for the lighting of large areas as in street illumination, as the light is produced at a very high candle-power.

THE MAGNETITE ARC LAMP.—The "magnetite" arc is so called from using magnetite, one of the oxides of iron as the negative electrode, and is used in the form of a powder tightly packed in a steel tube. The positive electrode is copper. The magnetite lamp has a white dazzling flame arc of great intensity, but small volume. The lamp is particularly adapted for street lighting. It is objectionable for

indoor lighting owing to the fumes which are given off during the consumption of the metallic electrode. Owing to the slow consumption of metal in the arc, frequent trimming is not required. For street lighting a lamp is built requiring 4 amperes and 78 volts at the arc.

378. Mercury Vapor Lamp and the Nernst Lamp.—The mercury vapor lamp, as its name implies, derives its light from the vapor of mercury in which the passage of an electric current causes a high state of incandescence. The lamp consists essentially of a glass tube, several feet in length, exhausted of air. A platinum wire is sealed in each end of the tube, the wire at the positive end connects with a piece of iron. At the negative end the platinum wire connects with metallic mercury forming the negative electrode. At starting the resistance between the negative electrode and the vapor is very high, and must be overcome before the lamp can be put in operation. Several methods are used to overcome this high resistance. One method sends a momentary high potential from an inductance coil through the lamp, which at the same time is connected to the low voltage mains. The high potential overcomes the high negative electrode resistance and the low voltage current follows. To aid the

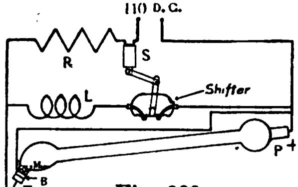

Fig. 382a.
Connections of automatic starting Mercury Vapor lamp.

starting of the lamp by this method a thin metallic band is attached to the outside surface of the lamp near to the negative electrode and connected by wire to the positive terminal of lamp. In the modern lamps of this type an automatic device is used for suddenly breaking the circuit through the inductance coil, thereby inducing the high potential which starts the lamp. Fig. 382a shows the connections of the lamp in which the automatic starting device is used. This device is termed a "shifter," and consists of an evacuated glass bulb containing mercury which is shifted by the action of an electromagnet S when the circuit is closed. When the circuit is closed the current also flows through the inductance coil L, the current through L is suddenly broken by the "shifter," inducing a momentary high potential which causes a spark to jump across from

the metallic band B to to the mercury M. This spark charges the mercury electrically and sets up sufficient vapor in the tube for the current to pass from P to N. The tube now glowing with a light of a decided greenish hue, and with sufficient current, the high negative resistance will not again make it appearance until the current is turned off; when, if it is desired to relight the lamp the same procedure has to be repeated. The shifter, inductance, resistance, etc., are contained in a cylindrical metal box from which the glass tube is suspended.

The simplest and least expensive method of starting the lamp, is to simply tilt the lamp until the two electrodes are brought in contact by a thin stream of mercury along the length of the tube, then allowing the lamp to return to normal position an arc is started causing the volatilization of the mercury, the vapor filling the tube, producing a light of the same tint as above. The light produced by this lamp has a very penetrating effect, bringing out the shape and contour of objects very clearly and for this reason the lamp is used to a great extent in draughting rooms, and for photography, etc. A lamp about 4 feet in length and 1 inch in diameter would produce about 700 candle-power with a current of 3.5 amperes at 110 volts. A certain amount of inductance and resistance is usually placed in series with the lamp, its function being to counteract any effect caused by a variation in voltage and thus permitting the lamp to operate more steadily.

THE NERNST LAMP.—In this lamp a filament, or *glower* as it is termed, of a high refractory rare earth is employed, and operated in the air. The glower is generally surrounded by a frosted globe, owing to its high candle-power. The material of which the glower is made is a non-conductor when cold, but becomes a conductor when hot, hence the glower must be heated before it will conduct electricity sufficiently to maintain it at a state of incandescence. The lamp is provided with a heater for this purpose, consisting of one or more thin porcelain tubes wound with fine platinum wire which in turn is held in place and protected from the intense heat of the glower by a refractory paste. This heater is automatically cut out of circuit by an electromagnet as soon as the glower lights. The action of the Nernst lamp is as follows: when the switch is turned on the cur-

rent flows through the heater, bringing it to a white heat; the proximity of the glower to the heater results in the glower becoming heated to a point at which it becomes a conductor, the current passing through it, and upon obtaining a certain value, the cut-out coil becomes energized, attracting the armature of the cut-out and opening the heater circuit which had been previously closed by the armature, the whole current now passing through the glower. Owing to the rapid decrease in resistance with the increased temperature of the glower, caused by the nature of the material of which it is made, it is difficult to control the current without a steadying resistance in series with it. A ballasting resistance made up of fine iron wire and mounted in a glass tube from which the air has been exhausted is connected in series with the glower. Iron wire is best adapted for the purpose, since it possesses the property of rapidly increasing in resistance with a rising temperature, thus compensating for the decrease in resistance of the glower and maintaining a fairly uniform current through it. In Fig. 382b is shown the interior arrangement of lamp and also the connections. The iron wire is enclosed in the glass tube to prevent its oxidization. Lamps are made having, 1, 3 and 6 glowers, for use on either direct or alternating current, the life of the glower on direct current is not as long as for alternating current, the life on a 60 cycle current is about 800 hours. The lamp gives a light of an excellent quality and with a frosted globe is very satisfactory for interiors or street lighting. Owing to the complicated mechanism and cost of glowers the lamp is somewhat expensive.

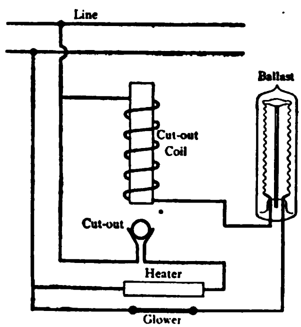

Fig. 382b.

Principle parts and connections in the Nernst Lamp.

379. Incandescent Lamps.—In an incandescent electric lamp the light is produced by heating to a state of incandescence, a high resistance solid conductor which is not readily fused by the passage of a current through it. The light giving element, termed the *filament*, is hermetically

sealed in a vacuum in a glass bulb, to prevent it from burning, ¶ 97. The filament is secured to two platinum wires sealed in one end of a glass tube; the platinum wires also make connection with two copper wires which in turn connect to the lamp base, Fig. 93, page 78. Platinum is used to pass through the end of the glass tube that is sealed because it expands and contracts at the same rate as glass, thus preventing the glass from breaking. The glass tube containing the platinum leading in wires and upon which the filament is mounted is sealed into the blown glass bulb of the ordinary shape; the bulb is connected by means of a glass stem (which is left at the upper end of bulb when it is blown), to an air-pump and a partial vacuum produced, the stem is then heated and sealed forming the pointed tip on the end of the lamp. The lamp base consists of two pieces of brass insulated from each other, secured to the lamp bulb by cement and arranged to hold the lamp securely when placed in a retaining *socket* connected to the main supply leads.

380. Lamp Filaments.—CARBON FILAMENT—The carbon filament is made in the following manner: absorbent cotton is dissolved in zinc chloride and hydrochloric acid forming a gelatinous mass a trifle thicker than molasses. This material is put in a bottle and forced through a small opening in the bottom, in thread form, by an air pressure from above, into a vessel containing alcohol which causes it to set and sufficiently harden for handling. After washing, the material is wound upon a drum and dried, when it possesses considerable strength. After being taken from the drums it is gauged for size and cut into suitable lengths and wound upon forms to produce the required shape, such as single coil, double coil, oval, or spiral filaments. The filaments are now *carbonized*, by being placed in a crucible surrounded with charcoal, so as to exclude the air, and then heated gradually in a furnace to a high temperature, at which it is allowed to remain until all volatile matter has been driven from the filament, leaving it in the form of a pure granular carbon thread. The filaments are now measured as to their length and diameter, and assorted for the different sizes of lamps in which they are to be used; the length of the filament is nearly proportional to the voltage, and the surface to the candle-power. The filament is next

treated in a gasoline gas, the object of which is to insure uniformity in resistance; the filament is placed in a closed vessel from which the air has been exhausted, and a gasoline vapor permitted to enter, a current of much greater value than the filament is intended for is sent through it. The intense heat of the filament caused by the current, decomposes the gasoline vapor depositing carbon on the filament, if one part of the filament is of a higher resistance than another its temperature will be correspondingly higher and more carbon will be deposited at that part. The treating apparatus is automatic in action, that is, when the filament has reached the desired resistance which is determined by measuring instruments inserted in the filament circuit, the current is automatically cut off. After the

Carbon or Gem. Tantalum. Tungsten.

Fig. 383.—Incandescent Lamps.

"treating" process, as it is termed, the filament looses the granular appearance, it having a smooth hard and apparently metallic surface, it is now ready for mounting upon the platinum leading in wires and is secured to them by a carbon paste.

THE METALLIZED FILAMENT.—The "metallization" of the carbon filament was the first step toward the production of a more efficient and light-giving element for use in incandescent lamps. The metallized filament is produced by heating the ordinary carbon thread in an electric furnace before and after the "treating" process, giving it the appearance and electrical characteristics of a metal. The lamp containing this filament was placed on the market under the trade name of the GEM lamp, and in appear-

ance is similar to the carbon lamp. Fig. 383. The most important advantage is the increase in efficiency, ¶ 383, over the carbon lamp, the filament has a *positive temperature coefficient,* that is, its resistance increases with an increase in temperature. The resistance of a filament changes by the addition, or substraction of a certain percentage of the cold resistance for each degree of temperature change. This percentage is called the *temperature coefficient,* ¶ 262. Lamps having *positive* temperature coefficients have their lowest resistance when cold, a carbon filament has a *negative* temperature coefficient, since its resistance is lowest when *hot.* See page 109.

TANTALUM FILAMENT.—The tantalum lamp was the first metallic filament lamp to reach a commercial state; the filament is drawn from the metal tantalum which has a very low resistance, requiring an extremely long filament. Owing to the long length of filament required and the fact that it softens to a considerable extent at incandescence it is necessary to support it about every inch to inch and a half of its length. This is accomplished by looping the filament back and forth through small hooks on the ends of radial wire supports, which extend from a supporting glass tree, Fig. 383. The tantalum filament has a positive temperature coefficient and gives more light than the carbon lamp at a higher efficiency than the Gem lamp.

381. The Tungsten Filament Lamp.—Tungsten or wolfram is a metallic element older than tantalum, it was discovered in 1781 and named from the Swedish "tung" (heavy) and "sten" (stone). It is not found native, but occurs as the tungstate of iron and manganese in the mineral "wolframite," and as the calcium tungstate. The pure tungsten metal comes in the form of a powder, is a bright steel gray, hard and very heavy, and was until recently characteristically brittle.

The first tungsten filament lamps were so fragile that the lamps could not be burned in any other than a vertical pendant position.

The first tungsten filaments were squirted through dies, similar to the carbon filaments, in one process tungstic acid was formed from wolframite, all the oxygen was then driven from the tungstic acid, bringing it to a state of

metallic tungsten, which was mixed with a suitable binder and squirted through dies into threads. Another method consisted of treating metallic tungsten with a strong boiling acid and alkali, alternately, washing it intermittently with water until converted into a colloid. The colloid is then precipitated, the liquid drawn off and the residue, consisting of a gelatinous mass is squirted. The filament having been squirted is dried in an oven, after which it is placed in an electric furnace, which readily removes the volatile parts. After being taken from the furnace an electric current is passed through it while it is occupying an atmosphere of inert gas. The result is the production of a thread of practically pure tungsten. Regardless of purity, the metal, however, showed no indication of ductility or pliability, it still retained its exceeding brittleness, requiring careful handling in the manufacture and use of the lamp in which it was used. Recently improved methods were discovered in the manufacturing of tungsten into wire, it being possible to draw tungsten metal into a wire .001 of an inch in diameter. To this latest achievement in metal filament lamps the trade name "Mazda" has been applied, signifying the highest development in metal filament lamps. The production of tungsten wire in great lengths produced a change in the construction of the lamps, a continuous filament is now used instead of fusing four or five filament loops together as was done in the first tungsten lamps. The filament is now wound upon spiders, Fig. 383, in a similar manner to the tantalum lamp, although the stiffer properties of the filament allow longer loops without danger of interlocking. The tungsten wire is clamped to the leading in wires, making a more flexible joint. Of all filaments developed thus far, those made of tungsten metal have proven the most ideal for incandescent lamps. This filament has a high positive temperature coefficient, insuring a remarkable steady candle-power over a comparatively wide range of voltage. It is a lamp of the highest efficiency, ¶ 383, producing a whiter light than the Gem lamp.

382. Commercial Rating of Incandescent Lamps.—Carbon lamps were originally rated according to the mean intensity of light produced in a horizontal direction. The label on the lamp gave the pressure, the corresponding

candle-power and the watts consumption. The standard carbon lamp in general use was rated as equivalent to the light given by 16 candles, and consuming from 50 to 60 watts. A 110-volt, 55-watt, 16-C. P. lamp requiring .5 ampere, Formula (63); the hot resistance is therefore 220 ohms, Formula (30); the watts per c. p. are 55 ÷ 16 = 3.4 watts. Carbons are made for various voltages up to 220 volts. For any particular voltage the higher the candle-power of the lamp the larger the area of its filament, the less its resistance, and consequently the more current it will take; with a constant candle-power the resistance of the filament increases with the voltage. The carbon lamp of to-day is rated in the total watts consumed, the voltage at which the lamp is to be burned is also given. The regular multiple burning 100 to 125 volt Gem, Tantalum and Mazda Tungsten lamps are rated in watts, and in addition, is marked on the label three voltages arranged in steps two volts apart; these voltages are termed the "top," "middle" and "bottom" voltages.

By this method of rating the lamps can be readily adapted to varying service conditions by the variation in efficiency, ¶ 383, provided, thus securing satisfactory life and economy in lighting. The rating of the lamp in *watts*, instead of in *candle-power*, was decided upon for the reason that there are so many candle-power values that may be taken, that the latter rating was misleading and did not give the true comparison between the illuminants so rated. For example, there is a mean candle-power value in a horizontal direction, a downward value, a mean spherical value and the values that would be obtained by the use of reflectors and shades. Moreover the watt is the unit used in the rating of all current consumption devices, as electrical energy for power and light is measured and sold on a wattage basis. However, the candle-power value has not been abandoned entirely, but is used when considering, only the illumination produced; the mean horizontal candle-power of a lamp may be obtained by dividing the watt rating by the efficiency (watts per c. p.), ¶ 383.

383. Life and Efficiency of a Lamp.—The efficiency of an incandescent lamp is usually expressed in "*watts per candle*" (w. p. c.), which is a ratio of the watts consumed to the mean horizontal candle-power given. The amount

of light given off by a lamp depends entirely upon the temperature at which it is operated. If a lamp is operated at a higher voltage than its rating, more light will be produced at a higher efficiency with the increased wattage consumption and temperature of the lamp, but with a corresponding decrease in the life of the lamp. With an increase in temperature the filament will disintegrate more rapidly, this is particularly true of the carbon filament. The disintegration of the filament takes place in all carbon lamps after they are in service for a period of time, and a blackened deposit appears upon the inside of the bulb, this with the disintegration causes a rapid falling off of candle-power, when the lamp should be replaced by a new one as the same amount of energy is being expended to produce less light. The economic or *useful* life of a lamp ceases long before the lamp is "burned out," the term "smashing point" is generally used to signify the end of the useful life of a lamp, which is reached when the candle-power falls to 80 per cent of its original value.

Rated according to their mean horizontal candle-power, the highest commercial efficiency of carbon lamps of 8 candle-power and over is 3.1 w. p. c., with a *useful* life of approximately 450 hours; of a Gem lamp, 2.5 w. p. c. with equal useful life; of a Tantalum lamp, 2 w. p. c. with a useful life of 800 hours on direct current, on alternating current life is uncertain; of a Mazda tungsten lamp, 1 to 1.5 w. p. c. with a life of 800 to 1000 hours. The variation in efficiency and life that can be obtained by operating a lamp at the three rated voltages is shown in the following table, which gives the average values of a Gem 50-watt lamp at "top," "middle" and "bottom" voltage, the three efficiencies at which the ordinary carbon filament lamp of corresponding life is operated is also shown.

Table of Average Values of 50 Watt Gem Lamp.

Voltage of Circuit same as	Total Watts	Mean Horizontal Candle-power	Watts per Candle-power	Hours Useful Life	Carbon Lamp of Corresponding Life
Top	50	20	2.5	450	16 c.p. 3. w.p.c.
Middle	48.5	18.3	2.65	640	16 " 3.3 "
Bottom	47.3	16.7	2.83	940	16 " 3.5 "

When the maximum efficiency is required lamps should be used with a "top" voltage corresponding to the voltage cf the circuit upon which it is to be used; whereas, if it is desired to operate the lamp at its lowest efficiency with longer life, a lamp having a "bottom" voltage corresponding to circuit voltage should be used. The practical efficiency at which carbon lamps should be used depends largely upon the regulation of the line voltage. With perfect regulation the high efficiency 3.1-watt carbon lamp may be used, but where the voltage fluctuates considerably the 3.5-watt lamp gives the best satisfaction. Owing to the positive temperature coefficient of the Gem, Tantalum, and Tungsten lamps they are not as sensitive to changes in line voltage as the carbon lamp, and is one of the advantages they possess over the carbon lamp. The Gem lamp gives a whiter light than the carbon, and it has already replaced thousands of carbon lamps, in fact, it is believed that it is only a question of time before the carbon lamp will become extinct. The development of tungsten into a filament that would withstand the ordinary vibrations and shocks to which lamps are subjected, have brought it into extensive general use, as it produces a still whiter light than the Gem with a reduction in the cost of current consumption which more than balances the extra cost of the lamp.

A 25-watt tungsten lamp, efficiency 1.25 w. p. c. giving 20 candle-power at one half the consumption of the 50-watt Gem producing the same C. P. With the substitution of tungsten lamps for carbon, in isolated generating plants, overloaded plants have been relieved, and in some plants the use of tungsten lamps has enabled one generating unit to do the work for which two were formally required. In the design of a new plant where tungsten lamps are to be used, a smaller generating plant is required than if carbon lamps are used, also reduction in size of wire carrying current to lamps, since they require less current than the carbon, resulting in a reduction of the first cost of installation.

384. Incandescent Lamp Circuits.—Incandescent lamps are usually operated from low voltage constant potential circuits and supplied by direct or alternating current. With a potential of 500 volts, as in street car serviee, the lamps are grouped in multiple series; for example

five 100-volt lamps in series being placed across the mains. A constant current series incandescent lamp system, for suburban street lighting, is sometimes employed, in which each lamp socket is provided with an automatic cut-out which short circuits the filament of the lamp in case of failure or burnout. In the series system the same current flows through all the lamps and is maintained constant, all lamps for such a system should have the same current rating. Low voltage lamps for series burning are constructed with a filament of large area to carry a current of from 5 to 10 amperes for carbon lamps. Low voltage Mazda tungsten lamps are also made for series burning, with current ranges of 1.75 to 8 amperes.

385. Potential Distribution in Multiple Lamp Circuits.—In a series circuit the drop on the lead wires does not interfere with the regulation of the voltage at the terminals of each lamp and the current being constant, the lamps burn at the normal candle-power. In multiple circuits, however, the drop on the lead wires is an important factor and requires that the lamps be so distributed, and the size of the wire so proportioned, that each lamp will receive approximately, the same voltage. For example, consider 200 110-volt incandescent lamps to be connected in parallel at various distances along a pair of mains extending 500 feet from the dynamo, and that the P. D. at the generator terminals is 112 volts; the lamps near the generator end of the mains will receive a higher potential than 110 volts and burn above candle-power with the result of frequent lamp renewals, while those near the distant end of the line will receive less than 110 volts and burn below candle-power. In order to overcome this difficulty, *centres of distribution* are planned in wiring construction, and the lamps are grouped so as to be supplied from these centres. Feed wires are run from the generator to the points of distribution and a constant potential maintained at these points by regulation at the generator. No lamps are connected to the feeders. Several sets of mains are run from these centers and supply sub-centers of distribution, to which the lead wires to the lamps are connected. The total drop or fall in voltage from the generator to the lamps in such a feeder and main system radiating from a central supply station, may be from 10 to 20 per cent of the generator

voltage, so that the dynamo is run at a correspondingly higher voltage than that required by the lamps. For example, the size of conductors may be so proportioned that when carrying full load their resistance produces a drop of 10 volts on the feeders, 3 volts on each set of mains radiating therefrom, and 2 volts on each set of sub-mains. Such a system of sub-division of the transmitting conductors is worked out upon an elaborate scale for lighting large and compact areas, as in the house and store service of cities supplied from a central generating plant. In the wiring of a house for about 50 standard 110-volt 16-C. P. lamps, the drop in voltage, at full load, will be about 2 per cent of the pressure supplied at the service mains. With an isolated plant in a large office building the drop may be 5 per cent of the generator voltage. In a building of 20 floors, a pair of main feeders may be run from the generator room to, say every 4 floors; there will thus be 5 sets of feeders, each being calculated to supply the given current with a 5 per cent loss on the line.

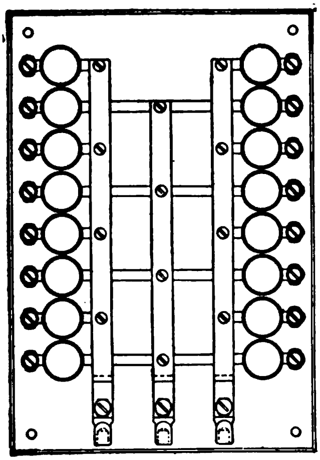

Fig. 384.

Eight Circuit—3-wire main—two wire branch Panel or Distributing Board. Plug Fuses shown by large circles.

The feeders terminate in cut-outs arranged in junction boxes, and subfeeders are carried to each of the four floors, these feeders terminating at a panel-board, Fig. 384, from which smaller branch circuits are run to the various lights on that floor. In calculating the size of wire for the smaller branch circuits a loss in volts of from $\frac{1}{2}$ to 1 per cent is usually allowed. In wiring buildings, wherever the size of wire is reduced a *fuse* must be inserted, the capacity of which does not exceed the permissible current carrying capacity of the smaller wire.

Fig. 384 shows a panel-board for distributing energy from a three-wire main feeder, the branch circuits being two

wire with a fuse in each branch wire since they are smaller than the main feeder. The panel-board shown consists of three vertical copper bus-bars furnished with lugs into which the feeders are soldered, the branch circuits of smaller copper bars are tapped off of the center vertical bar and either side bar, so that the lamps receive their proper potential, see ¶ 388. The copper bus-bars are mounted on slate or marble. Where the energy is distributed to lamps with the *two-wire* main feeders, subfeeders, etc., a two-wire main with two-wire branches panel-board is used.

Most Central Stations distribute their electrical energy for lighting and power with the three-wire system, ¶ 388, as it is more economical where the energy is distributed over large areas.

386. Loss on Transmission Lines.—*The weight of copper wire required for conducting current to lamps or motors, with the same loss on the transmitting line, is inversely proportional to the square of the voltage supplied to the lamps or motors.* For example, suppose 50000 watts (50 K. W.) are transmitted to some distant centre of distribution; 1000 watts the permissible loss on the line; the weight of copper required, when the energy is delivered at 50 volts, to be 1000 pounds; then the comparative weight of copper for other voltages according to the above law is given as follows:

Energy Transmitted.			Loss on the Line.			Copper Required.
K. W.	Volts.	Amperes.	Volts Drop.	Amperes.	Watts.	Pounds.
50	100	500	2	500	1000	1000
50	200	250	4	250	1000	250
50	500	100	10	100	1000	40
50	1000	50	20	50	1000	10

As the voltage, at which the above energy is transmitted increases, the current to be conducted on the line decreases, thereby decreasing the size of the wire, increasing its resistance and the line drop. As the drop on the line increases the current is proportionally reduced and the line loss the same.

In the electrical transmission of power to long distances,

economy of copper is attained by transmitting the energy at a very high voltage and reducing it to a working value, within the danger limit, at the receiving station. For example, several thousand horse power are transmitted from Niagara Falls to Buffalo, about 26 miles, at 20000 volts. The current is an alternating one, and at Buffalo the voltage is reduced by transformers to the proper values for lighting and power purposes. In a western transmission plant the power is transmitted at 80000 volts with a greater reduction in weight of copper but requiring special insulating materials for such a high potential.

387. Incandescent Wiring Calculations.—The simplest method for calculating the size of wire required to conduct current to any given number of lamps, with any permissible drop in voltage on the line, is to find the resistance of the line by Ohm's Law and then consult the wire gauge table and the table of safe carrying capacities, pages 113 and 266. See also ¶ 239.

A general formula to find the size of wire directly in circular mil area required to carry any direct current any distance, with any given loss on the line, is derived by combining Formulæ (22) and (30) as follows:

$$\text{By Formula (22)}\ R = \frac{K \times L}{C.M.}. \quad (30)\ R = \frac{E}{I}.$$

$$\text{Therefore } \frac{K \times L}{C.M.} = \frac{E}{I},$$

$$\text{and } E \times C.M. = K \times L \times I,$$

$$\text{or } C.M. = \frac{K \times L \times I}{E}.$$

Copper being generally used as the conductor, $K = 10.79$, and this formula becomes

$$C.\ M. = \frac{10.79 \times L \times I}{E} \quad \ldots\ldots\ldots \quad \mathbf{(110)}.$$

Where C. M. = circular mil area;
K = 10.79 = resistance 1 mil-foot of copper wire;
L = length of circuit in feet;
I = current in amperes;
E = volts drop on the line.

To Find the Size of Copper Wire in Circular Mils, to Conduct any Given Direct Current, Any Distance With a Given Drop on the Line:

*The size of wire to transmit an alternating current may be approximately determined by using the constant (13) instead of 10.79 in Formula (110). See note, page 450.

Multiply the total length of the line, in feet, by the resistance of a mil-foot, 10.79, and this product by the current, in amperes, to be conducted; divide this product by the volts lost on the line. Formula (110).

The circular mil area so found must be compared with the table of carrying capacities, page 266. By using a very excessive drop on the line the circular mil area calculated by Formula (110) in some cases would be much too small for the current to be conducted, and hence the necessity of a check upon the calculations, by the table of carrying capacities. *Usually the distance from the generator to the centre of distribution is given for the two-wire multiple system, and this distance must be multiplied by 2 to obtain the total length of the circuit, L in Formula (110).*

Prob. 134. One hundred 55-watt 110-volt lamps are connected in parallel and to a centre of distribution located 125 feet from the dynamo which generates 113 volts P. D.; the potential at the distributing centre is 111 volts. What size wire is required for the feeder?

By Formula (63) $I = \frac{W}{E} = \frac{55}{110} = .5$ ampere per lamp.

$100 \times .5 = 50$ amperes to be conducted.

$113 - 111 = 2$ volts drop on the line.

By Formula (110) $C.M. = \frac{10.79 \times 125 \times 2 \times 50}{2} = 67437$ C. M.

$L = 125 \times 2 = 250$ feet, $I = 50$ amperes, $E = 2$ volts.

Consulting the table, page 113, the size of wire nearest to 67437 C. M. is No. 2 B. & S. = 66370, which is smaller than that required. Always use the next larger size of wire to that calculated, or in this problem a No. 1 B. & S., which will give a little less drop than 2 volts. Consult the safe carrying capacity table, page 266, and it is found that No. 1 will carry 107 amperes, and will thus readily carry 50 amperes. A much smaller wire could have been used in this problem, as a No. 5, which carries 54 amperes, but the line drop and loss would then have been correspondingly larger, since the resistance of the circuit is increased. The line loss is a constant factor—that is, the watts, $50 \times 2 = 100$, lost on the line in the above problem are constant, so long as this load is constant, and will cost each year a certain sum for this loss, while the cost of the line installation is only the first cost. The most economical conductor is installed when it is possible to make the yearly cost of the

power lost on the lines equal to the interest on the value of the copper invested. The *volts lost* or drop on any circuit may be measured by a voltmeter, ¶ 231, or calculated by Formula (29), when the current and resistance of the circuit are known, or from the following Formula, obtained by transposing Formula (110):

$$E = \frac{10.79 \times L \times I}{C.\ M.} \ldots\ldots\ldots\ldots\ldots\ldots (111).$$

To Find the Volts Lost or Drop in Any Circuit (of copper wire):

Multiply 10.79 by the length of the circuit in feet, and this product by the current, in amperes; divide this result by the circular mil area of the wire.

Prob. 135: An ammeter, connected in series with a circuit of copper wire 200 feet long, indicates 25 amperes; the size of wire measured by a wire gauge is No. 10 B. & S. What is the drop on the line?

By Formula (111) $E = \frac{10.79 \times L \times I}{C.M.} = \frac{10.79 \times 200 \times 25}{10381} = 5.2$ volts.

To Find the Power Lost on Any Line:

Multiply the volts drop on the line by the current flowing through it, $W = E \times I$, Formula (62).

Prob. 136: (a) What power is lost on the line in Prob. 134? (b) What is the cost of this loss for 10 hours per day for 365 days at 10 cents per kilowatt hour?

By Formula (62) $W = E \times I = 2 \times 50 = 100$ watts (a).

By ¶ 223. $365 \times 10 = 3650$ hours $\times$ 100 watts $= 365000$ watt-hours.

$\frac{365000}{1000} = 365$ K. W.-hours.

$365 \times .10 = \$36.50$ (b).

388. The Three-Wire System.—In the three-wire multiple system two dynamos are joined in series, and the lamps connected between a centre or neutral wire joined to the junction of the machines, and the positive and negative wires of the system, Fig. 385. When all the lamps are in circuit, Fig. 385, no current flows through the middle wire, and it can be disconnected at the generators without affecting the system. If only three lamps are connected on the No. 1 side of the system, then current for the two extra lamps not paired flows through the middle wire from the + brush of No. 2 generator. The middle wire is now positive. If three lamps are out on the No. 2 side of the system,

then current for the three lamps on the No. 1 side flows from the + terminal of generator No. 1 and returns to it by the middle wire, which is now negative. The middle wire, therefore, may have no current flowing through it, or current flowing in either one direction or the other, depending upon whether the lamps on both sides of the system are accurately balanced, which is the aim in practice. For this reason it is called the neutral wire. When all the lamps are turned off on one side of the system the neutral wire carries the current for all the lamps on the other side. Motors wound for 220 volts are connected to the two out-

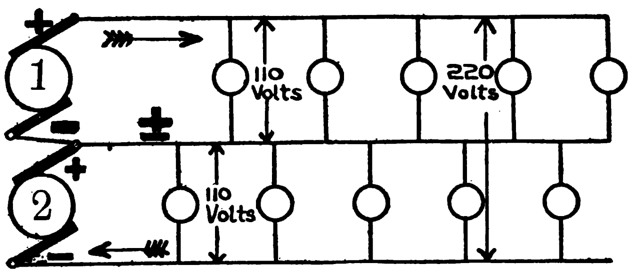

Fig 385.—Incandescent Lamps Operated in Parallel from the Three-Wire System.

side wires and do not, therefore, interfere with the balancing of the system.

The electromotive force is double that of the ordinary two-wire multiple system and the current required for any given number of lamps is reduced to one half that required on the two-wire system. The chief advantage of the system is the saving effected in copper by its use, about $\frac{3}{8}$ of the weight of copper being required, as compared with the two-wire system. For example, suppose 1000 pounds of copper are required for a given number of lamps operated from the 110-volt two-wire system: if the voltage be doubled, the weight of copper required is $\frac{1}{4}$ as much as before for the same loss, ¶ 386, or 250 pounds for the two wires. Now since in the three-wire system one extra wire is required, if it is made the same size as the others, as is often the case, it will weigh $\frac{1}{2}$ of 250 pounds, or 125 pounds, and the three wires will weigh 375 pounds, or only $\frac{3}{8}$ of the weight of copper is required by this system. The joint resistance of 10

110-volt, 220 ohm lamps on the two-wire system is 22 ohms, Formula (43), while on the three-wire system the joint resistance of the same number of lamps, two in series, 5 groups in parallel, is 88 ohms. The joint resistance of the lamps being four times greater on the three-wire system than on the two-wire system, the resistance of the lead wires will also be four times greater for the same percentage of loss, and therefore only one-fourth as large as those required for the two-wire system.

TO FIND THE SIZE OF WIRE REQUIRED FOR THE THREE-WIRE SYSTEM:

Find the size of wire required for the same number and kind of lamps on the two-wire system, by Formula (110), and divide the number of circular mils, so obtained, by 4, Formula (112).

$$C.\,M. = \frac{10.79 \times L \times I}{4 \times E} \text{...............} \textbf{(112)}.$$

Prob. 137: The lamps referred to in Prob. 134, page 430, are to be operated from the three-wire system. What size of wire will be required?

$$\text{By Formula (112)} \quad C.\,M. = \frac{10.79 \times L \times I}{4 \times E} = \frac{10.79 \times 125 \times 2 \times 50}{4 \times 2}$$
$$= 16859 \text{ C. M.}$$

From Table VII, page 113, No. 8 B. & S. = 16510 C. M. and from Table XV, page 266, No. 8 will carry 33 amperes. Since the current on the three-wire system is one-half that for an equivalent number of lamps on the two-wire system, the No. 8 wire in this problem will only carry ½ of 50, or 25 amperes, and is therefore sufficiently large. The neutral wire may be made the same size as the outside wires; sometimes it is made one half as large since it is hardly probable that all the lamps on one side of a well balanced three-wire system will be out and the others all burning. A further increased saving of copper is then attained.

389. Motor Wiring Calculations.—TO FIND THE SIZE OF WIRE, IN C. M., TO TRANSMIT ANY GIVEN HORSE POWER ANY DISTANCE, WHEN THE VOLTAGE AND EFFICIENCY OF THE MOTOR ARE KNOWN:

Multiply the rated horse power of the motor by 746 then by the length of the circuit in feet and then by 10.79; divide this result by the product of the voltage required by the motor and the drop on the line multiplied by the efficiency of the motor, Formula (113).

Average motor efficiency.

1 H. P.	75 per cent.
3 H. P.	80 "
5 H. P.	80 "
10 H. P.	90 "

Let E = voltage required by motor;
e = drop on the lines;
H. P. = horse power of motors;
% M = efficiency of motor, expressed as a decimal;
then from Formula (110) is derived,

$$\text{C. M.} = \frac{\text{H. P.} \times 746 \times L \times 10.79}{E \times e \times \%M} \quad .. (113).$$

Prob. 138: What size of wire is required to conduct current to a 220-volt 5-H. P. motor located 150 feet from the meter; the drop on the line is to be 5 volts and the efficiency of the motor is 80%?

By Formula (113) $\text{C. M.} = \frac{\text{H. P.} \times 746 \times L \times 10.79}{E \times e \times \% M}$

$$\frac{5 \times 746 \times 150 \times 2 \times 10.79}{220 \times 5 \times .80} = 13720 \text{ C. M.}$$

H. P. 5, 80% = .80, L = 150 × 2 = 300 feet, E = 220 volts, e = 5 volts.

From Table VII, page 113, No. 8, B. & S. = 16510 C. M. The motor requires 21 amperes, calculated by Formula (114) in Prob. 139; and from Table XV, page 266, the carrying capacity is 33 amperes, so that No. 8 is the proper size of wire.

To Find the Current Required by a Motor When the Horse Power, Efficiency, and Voltage are Known:

Multiply the H. P. by 746 and divide this product by the voltage of the motor multiplied by its efficiency, Formula (114).

$$I = \frac{\text{H. P.} \times 746}{E \times \%M} \quad .... (114).$$

Prob. 139: What current will the motor in Prob. 138 receive?

By Formula (114) $I = \frac{\text{H. P.} \times 746}{E \times \% M} = \frac{5 \times 746}{220 \times .80} = 21$ amperes.

H. P. = 5, E = 220 volts, % M = 80 = .80.

To Find the Horse Power Developed by a Motor:

Multiply the pressure applied to the motor terminals by the current supplied to it and multiply this product by the efficiency of the motor; divide this result by 746, Formula (115).

$$\text{H. P.} = \frac{I \times E \times \%M}{746} \quad .... (115).$$

This formula is obtained by transposing Formula (114).

Prob. 140: A current of 45 amperes is supplied to a motor, having an efficiency of 85 per cent., under a pressure of 220 volts. What horse power is developed by the motor?

By Formula (115) $H.P. = \frac{I \times E \times \% M}{746} =$

$$\frac{45 \times 220 \times .85}{746} = 11 \text{ H.P.}$$

$I = 45$ amperes, $E = 220$ volts, $\% M. = 85 = .85$.

QUESTIONS.

1. What is the chief distinction between an arc and an incandescent lamp?
2. What is the crater of an arc, and where is it located? Give sketch.
3. What is the relative consumption of carbon in a lamp used, (*a*) on direct current circuits; (*b*) on alternating current circuits?
4. From what part of the arc is the most light emitted and what is the general direction of its reflection?
5. What is your answer to question 4 when the arc is fed by an alternating current?
6. What is the cause and disadvantage of a carbon arc that flames?
7. What adjustment is required for an arc lamp which hisses badly?
8. What is the advantage of cored carbons over solid carbons for arc lamps fed from alternating current circuits?
9. Why is the drop, in volts, across a normal arc between cored carbons less than when solid carbons are used?
10. Describe the principle of action in a differential arc lamp.
11. What is the difference between an inclosed and an open air arc?
12. State two advantages of the inclosed arc lamp.
13. Why are arc lamps for street lighting generally operated in series?
14. What are the advantages of the tungsten lamp over the carbon?

PROBLEMS.

1. A 110-volt 16-C. P. carbon lamp requires 55 watts. Give the following: (*a*) Efficiency of lamp; (*b*) lamps per H. P.; (*c*) cost of burning the lamp for 100 hours if the energy costs 10 cents per K. W. hour? *Ans.* (*a*) 3.4 W. P. C.; (*b*) 13 lamps; (*c*) $0.55.
2. A 25-watt Mazda lamp has an efficiency of 1.25 watts. Give the following: (*a*) candle-power produced; (*b*) lamps per H. P.; (*c*) cost of burning this lamp for 100 hours, if the energy costs 10 cents per K. W. hour? *Ans.* (*a*) 20 C. P.; (*b*) 29 lamps; (*c*) $0.25.
3. Two hundred 55-watt 110-volt lamps are connected in parallel and are fed from a centre of distribution located 100 feet distant from the generator; 2½ volts are to be lost on the main feeders. What size of wire will be required? *Ans.* No. 0 B. & S.
4. If 25-watt Mazda lamps were used in problem 3, what size wire would be required, allowing 2 volts loss on line? *Ans.* No. 3 B. & S.
5. A series arc circuit, 5 miles in length, is constructed of No. 6

B. & S. wire and carries 10 amperes. (*a*) How many volts drop on the line? (*b*) What power is lost on the line? (*c*) What is the yearly cost of the power lost on the line, running 10 hours a day for 365 days at 10 cents per K. W. hour? *Ans.* (*a*) 108.5 volts; (*b*) 1085 watts; (*c*) $396.025.

6 The lamps in problem 3 are to be supplied from a three-wire multiple system. What size wire will be required? *Ans.* No. 5 B. & S. (when checked by Table XV).

7. With 6 volts drop on the line what size wire is required to carry current for a 10-H. P. 220-volt motor, located 150 feet from the source of supply; efficiency 90%? *Ans.* No. 7 B. & S.

8. What current will the motor in problem 7 receive? *Ans.* 37 amp.

LESSON XXXI.

ALTERNATING CURRENTS.

Principles of Alternating Currents—Theory of Alternating Currents—Sine Curves—Frequency, Alternations and Cycles—Inductance—Reactance—Impedance—Graphical Illustrations of Impedance, Reactance and Resistance—Capacity—Peculiarities Due to Self-Induction and Capacity—Impedance Due to Inductance, Capacity and Resistance—Ohm's Law for Alternating Current Circuits—Impedances in Series—Impedances in Parallel—Effective Values Alternating Currents and E. M. F's.—Components of Impressed E. M. F.—Angle of Lag and Phase Difference—Determination of Power.

390. Principles of Alternating Currents.—A continuous or direct current is one of uniform strength always flowing in one direction, while an *alternating current* is continually changing both its strength and direction. The various principles and facts concerning direct current distribution which have been explained in the preceding lessons apply also to alternating current systems. But in addition to the simple phenomena due to the resistance, which occur with direct currents, there are certain additional factors that must be considered in connection with alternating currect transmission.

The flow of a direct current is entirely determined by the ohmic resistance of the various parts of the circuit. The flow of an alternating current depends upon not only the resistance, but also upon any *inductance* (self or mutual) or *capacity* that may be contained in or connected with the circuit. These two factors, inductance and capacity, have no effect upon a direct current after a steady flow has been established, which usually requires only a fraction of a second. In an alternating current circuit either or both of them may be far more important than the resistance and in some cases may entirely control the action of the current. Alternating current problems involving the consideration of three factors are usually more complicated and difficult to solve than those relating to direct currents. By an extension of the principles and methods employed for direct cur-

rents, however, alternating current systems can be designed correctly and without great difficulty.

The only reason practically for employing alternating currents for electric lighting and power purposes is the economy effected in the cost of transmission which is accomplished by the use of high voltages and transformers. It has already been shown (page 386) that the cross section of a wire to convey a given amount of electrical energy in watts with a certain "drop" or loss of potential in volts, is inversely proportional to the square of the voltage supplied; that is, it requires a wire of only one quarter the cross-section and weight if the initial voltage is doubled. The great advantage thus obtained by the use of high voltages can be realized either by a saving in the weight of wire required or by transmitting the energy to a greater distance with the same weight of copper.

391. Theory of Alternating Currents.—Under the theory of dynamos it was explained that each armature coil of a dynamo tends to generate an E. M. F. which rises from zero to a certain maximum value and falls to zero again, then reverses in direction, rising to a maximum value and returning to zero, ¶¶291, 321. In Fig. 386 let us suppose that the line OP revolves at a uniform rate about the point O, that is, one end remains fixed at O while the point P moves around the circle in the direction of the arrow. The angle A will then be constantly changing; when point P is at a, that is, when the point P is just starting on a revolution, the angle A is zero, because OP lies along Oa. When P reaches 5 angle A has become 90°; when it reaches 10, 180°; 15, 270°; and 20, 360°; or in other words P has reached the starting point again, having made a complete revolution. Now let us imagine the point P to be an armature coil revolving between the poles NS; by following the curve we note that as the coil, or the point P, moves from a to 5 the induced E. M. F. gradually rises from zero at a, to its maximum value at 5 in the circle or 90° from a, which it should since at 5, 90°, the coil is in the position of maximum induced E. M. F.; then moving from 5 to 10 the E. M. F. gradually falls to zero at 10; continuing the revolution of the coil we find (observing the curve) that the E. M. F. gradually rises from zero at 10 to its maximum value at 15, 270°, and then falling to zero, *but in the opposite direction*, since the coil is now under the opposite or S pole.

The variation of an alternating current may always be represented by a wavelike curve as shown in Figs. 312 and 386.

In order to study the effects of an alternating current it is necessary to know the law according to which this curve varies. A consideration of the manner in which the curve

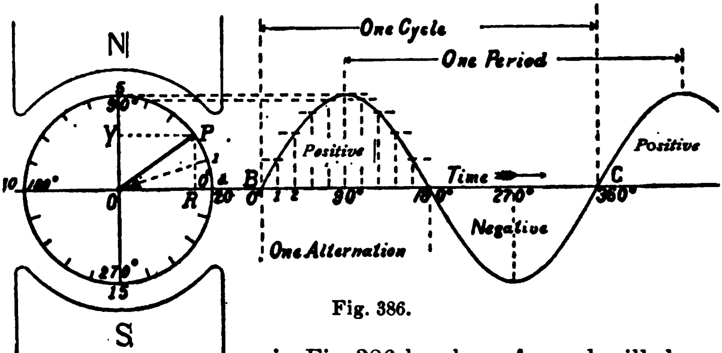

Fig. 386.

in Fig. 386 has been formed will show that the ordinate on any point P is proportional to the sine of the abscissa of that point. Hence it is called a *Sinusoid* or *sine curve.*

The ideal pressure curve from an alternator is sinusoidal. Commercial alternators, however, do not generate true sinusoidal pressures, but they so closely resemble the curve depicted in Fig. 386 that for all practical purposes the sine curve can with propriety be applied to those of practice.

392. Sine Curves. —

The sine curve or curve of E. M. F. is plotted as follows: Take a horizontal line such as that marked *Time*, Fig. 386. To draw the E. M. F. curve, we must take a length along the horizontal line *Time*, such as B to C: this may conveniently be made equal to half the length of the circumference of the circle in which P moves. This length is then equally divided up, being proportional to circumferential distances and may be drawn to any scale. We then have a straight line with subdivisions representing the distances moved by P around the circle or, what is the same thing, the angles made by the radius with its first position in its revolution around the center O; and these divisions may also be taken to represent the time it takes P to turn through the various values of the angle A. Suppose P has reached the point 1, take a distance along the time base equal to half the circumferential distance a1, and at that point erect a perpendicular; where this cuts a horizontal line drawn through point 1 on the circle, we get one point on the curve. In the same way for position 2 we take half the distance along the circumference a2 and

mark this off on the time base, then erect a perpendicular and where the latter cuts a horizontal line drawn through 2 on the circle, we get the second point on our curve.

This operation being repeated for different positions of P around its circular path (4, 5, 6, etc.), a series of points is obtained, which, when connected, are found to lie on a wavy line called the *sine curve.*

The wave is known in trigonometry as a *sine wave* for the following reason:

The ratio of PR to OP is known as the sine of the angle A, OP remains constant while PR increases and decreases as P revolves around the center O. The line PR is therefore always proportional to the sine of the angle A, and the perpendicular line, or ordinate, that determines the height of the wave curve at any point is equal to the value of the ordinate or perpendicular PR corresponding to that point formed by drawing the horizontal line, abscissa, PY. The wave, therefore, at any point, has a height which is proportional to the sine of the angle that corresponds to that point, hence the name sine wave.

In the figure, the line PR is the sine of the angle A, and the ratio $\frac{PR}{OP}$ represents the sine value of the angle A.

393. Frequency — Alternations — Cycles. — When, as stated above, the alternating current or E. M. F. has passed from zero, to its maximum value, to zero, in one direction, then from zero, to its maximum value, to zero, in the other direction, the complete set of values passed through repeatedly during that time is called a *cycle.* This cycle of changes, which is represented by the sine curve depicted in Fig. 386, constitutes a complete *period,* and since it is repeated indefinitely at each revolution of the armature the currents produced by such an E. M. F. are called *periodic currents.* The number of complete periods in one second is called the *frequency* of the pressure or current. In Fig. 386 a *period* is represented by the time elapsing from one positive maximum to the next positive maximum, although it makes no difference whether one considers a period or cycle to begin when the E. M. F. curve is at the horizontal or zero line, or when it is maximum or at some other point; a cycle or period comprises the succession of changes which occur from any one point on the curve to the next point where the curve indicates the same character of E. M. F. or current. The time elapsing from 0° to 360°, Fig. 386, would constitute a period, since a period represents one complete cycle of events, or two reversals in the direction of the current.

The term *frequency* is applied to the number of cycles

completed in a unit of time—one second. The word *alternations* is sometimes used to express the frequency of an alternator, meaning the number of *alternations per minute*. In practice the frequency is usually expressed in *cycles*. An alternation is half a period or cycle. In Fig. 386, from 0° to 180° is one alternation; since the current changes its direction at each half cycle, it follows that the number of alternations or reversals is twice the number of cycles.

If the current from an alternator performed the cycle of events depicted in Fig. 386 sixty times a second, it would be said to have a *frequency* of 60 *cycles*, which would mean 120 alternations per second, or 120x60 seconds=7200 alternations per minute.

The frequency of an alternating current is always that of the E. M. F. producing it.

TO FIND THE FREQUENCY IN CYCLES OF THE PRESSURE OR CURRENT OF ANY ALTERNATING CURRENT GENERATOR, MULTIPLY THE NUMBER OF PAIRS OF POLES BY THE SPEED OF THE ARMATURE IN REVOLUTIONS PER SECOND.

Let $f =$ cycles;
$P =$ number of pairs of poles;
$N =$ speed (revolutions per minute).

$$f = P \times \frac{N}{60} \quad . \; . \; . \; . \; . \quad (\mathbf{116}).$$

TO FIND THE ALTERNATIONS OF ANY ALTERNATING CURRENT GENERATOR:

Multiply the number of poles by the speed in revolutions per minute.

Let $f_1 =$ alternations;
$P_1 =$ number of poles.

$$f_1 = P_1 \times N \quad . \; . \; . \; . \; . \; . \quad (\mathbf{117}).$$

Prob. 141: (*a*) What would be the frequency (in cycles) of the current furnished by an alternator having 10 poles and running at 1600 revolutions per minute? (*b*) What would be the alternations of the current?

(*a*) By Formula (116) $f = P \times \frac{N}{60} = 5 \times \frac{1600}{60} = 5 \times 26.6 = 133$ cycles.
10 poles = 5 pairs.

(*b*) By Formula (117) $f_1 = P_1 \times N = 10 \times 1600 = 16000$ alternations.

Unless otherwise specified, *frequencies* are in the term of cycles, thus: a frequency of 60 means 60 cycles. The frequency of commercial alternating current depends upon the work it

is expected to do. For power a low frequency is desirable, frequencies for this purpose varying from 60 down to 25.

For lighting work frequencies from 60 to 125 are in general use. Very low frequencies cannot be used for lighting owing to the flickering of the lamps. A number of central stations have adopted a frequency of 60 as a standard for lighting and power transmission.

394. Inductance.—Most of the peculiarities that alternating current exhibits, as compared with direct current, are due more or less to the fact that an alternating current is constantly changing, whereas a continuous current flows uniformly in one direction. As has been shown in previous lessons, when a current flows through a wire it sets up a magnetic field around the wire, and since the current changes continually this magnetic field will also change. Whenever the magnetic field surrounding a wire is made to change, an E. M. F. is set up in the wire, and this induced E. M. F. opposes the current. For example, when the current rises

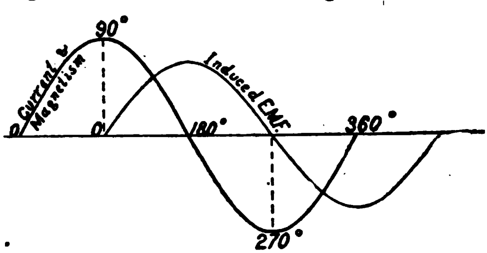

Fig. 387.

in the positive direction, the magnetism increases in, let us say, the clockwise direction about the conductor; after the current passes the maximum value and begins to decrease, the lines of force commence to collapse, reaching zero value when the current reaches zero; then when the current rises in the negative direction the magnetic lines expand in the counter-clockwise direction and so on. The result is that the counter E. M. F. of self induction, instead of being momentary, as when the current is made and broken through a conductor, is continuous, but varies in value like the applied E. M. F. and the current. The value of an induced E. M. F. is proportional to the rapidity with which lines of force are cut by the conductor, and as the lines of force vary most rapidly when passing the zero point (changing from + to −) or *vice versa*, the induced E. M. F. is maximum at that moment.

When the current, and therefore the magnetism, is at the maximum value in either direction, its strength varies very little within a given momentary period of time, and consequently the *induced* E. M. F. is zero at the moment the current and magnetism is at maximum, the E. M. F. of self-induction not rising and falling in unison with the applied E. M. F. and the current, but lagging behind the current exactly a quarter of a cycle, as shown in Fig. 387.

This property of a wire or coil to act upon itself *inductively* (self-induction) or of one circuit to act inductively on another independent circuit (mutual induction) is termed *Inductance.*

The *Unit* or *Coefficient* of inductance is called the *henry*, the symbol for which is L, ¶ 296.

Many devices met with in alternating current work have this property of inductance. A long transmission line has a certain amount of it, as have induction motors and transformers.*

395.—Reactance. From ¶¶ 297, 298, 394 we learn that the effect of *inductance* in an alternating current circuit is to oppose the flow of current on account of the counter E. M. F. which is set up. This opposition may be considered as an apparent additional resistance, and is called *reactance* to distinguish it from ohmic resistance.

Reactance is expressed in ohms, like resistance, because it constitutes an opposition to the flow of the current. Unlike resistance, however, this opposition does not entail any loss of energy because it is due to a counter pressure and is not a property analogous to friction. Its effect in practice is to make it necessary to apply a higher E. M. F. to a circuit in order to pass a given current through it than would be required if only the resistance of the circuit opposed the current. The value of the *reactance* due to inductance may be expressed in the formula

$$X = 2\pi fL \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \mathbf{(118)}.$$

where X = reactance;
L = inductance (henrys);
f = frequency (cycles);
π = 3.1416.

* The effect of inductance on transmission lines is to increase the size of wire, as in addition to the E. M. F. to overcome resistance, some E. M. F. must be used to overcome the inductance of the line, necessitating a larger size wire in order to keep the drop on the line within the specified limits. See note, page 429.

Transposing Formula (118) we have

$$\text{Inductance} = \frac{\text{reactance}}{2\pi f}, \text{ or } L = \frac{X}{2\pi f} \;.\;.\; \textbf{(119)}.$$

Prob. 142:—What would be the reactance of a coil of wire having an inductance of .02 henry when connected to an E. M. F. of 100 volts, 60 cycles?

By Formula (118) $X = 2\pi fL = 6.28 \times 60 \times .02 = 7.536$ ohms; $2\pi = 6.28$.

Prob. 143:—What would be the inductance of a coil which has a reactance of 8 ohms when connected to an E. M. F. of 120 cycles?

By Formula (119) $L = \frac{X}{2\pi f} = \frac{8}{6.28 \times 120} = \frac{8}{753.6} = .01$ henry.

396. Impedance.—The circuits met with in practice always have resistance as well as inductance and in most cases the former cannot be neglected.

The combined effect of resistance and inductance is called *impedance* to distinguish it from the other two, and the value in ohms (total resistance) for any circuit may be expressed in Formulæ (120), (121). The symbol for *impedance* is Z.

$$\text{Impedance} = \sqrt{\text{Resistance}^2 + \text{Reactance}^2}$$
$$\text{or } \mathbf{Z} = \sqrt{\mathbf{R}^2 + (\mathbf{2\pi f L})^2} \;.\;.\;.\; \textbf{(120)}.$$
$$\text{or } \mathbf{Z} = \sqrt{\mathbf{R}^2 + \mathbf{X}^2} \;.\;.\;.\;.\;.\;.\; \textbf{(121)}.$$

Prob. 144. What would be the impedance of a coil of 4 ohms resistance and 8 ohms reactance?

By Formula (121) $Z = \sqrt{R^2 + X^2} = \sqrt{4^2 + 8^2} = \sqrt{16 + 64} = 8.94$ ohms.

GIVEN IMPEDANCE AND OHMIC RESISTANCE TO FIND THE REACTANCE:

$$\mathbf{X} = \sqrt{\mathbf{Z}^2 - \mathbf{R}^2} \;.\;.\;.\;.\; \textbf{(122)}.$$

GIVEN IMPEDANCE AND REACTANCE TO FIND OHMIC RESISTANCE:

$$\mathbf{R} = \sqrt{\mathbf{Z}^2 - \mathbf{X}^2} \;.\;.\;.\;.\;.\; \textbf{(123)}.$$

397.—Graphical Illustrations of Impedance, Reactance and Resistance.—The relations expressed by Formula (120) may be represented by a right angle triangle, ABC, Fig. 388 (a). The true ohmic resistance (R) is laid off on a convenient scale to form the base line, the reactance $2\pi fL$ (X) is laid off also in ohms to form the perpendicular, and the impedance in ohms is found by measuring the hypothenuse of the triangle, since it is equal to the square root of the sum of the squares of the other two sides. This is merely a mathemati-

cal coincidence, however, resulting from the use of the sine curve as the basis of alternating current calculations. Such a triangle is frequently used to represent the relations between resistance, reactance and impedance and also for convenience in getting at other values.

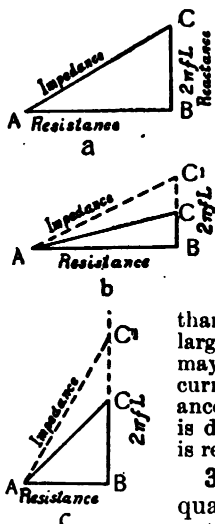

Fig. 388.

When the reactance is small compared with the resistance, it has very little effect. This is shown in Fig. 388 (b). The line BC is short compared with AB and the impedance represented by AC is not much larger than the resistance AB. When the reactance is double and made equal to BC[1] the impedance is not much increased.

When the reactance is large compared with the resistance, the impedance is much greater than the resistance. This is shown in Fig. 388 (c). If the reactance is doubled and made equal to BC[1], the impedance AC becomes nearly twice as large, and the current at a given E. M. F. would be only a little more than half as great. In coils where self-induction is large compared to the resistance, the resistance may be entirely neglected, and we may say that the current equals the E. M. F. divided by the reactance. If the frequency is doubled, the reactance is doubled and the current at the same potential is reduced one-half.

398. Capacity.—Capacity is the third quantity which affects the flow of an alternating current and which, like self-induction, does not enter into the consideration of the flow of direct current. This physical quantity may be noted in the case of the *electrostatic* capacity of a Leyden jar or a condenser and is measured in the terms of the farad as a unit, being the capacity of a condenser which will contain one coulomb of charge at a potential of one volt. Since this unit is much too large for ordinary use a smaller one, the *microfarad*, or millionth part of a farad, is generally used.

If we take a number of sheets of tin foil and interweave them with a corresponding number of slightly larger sheets of waxed paper and then press the whole mass tightly together, we have an electrical *condenser*, ¶ 303. The construction of a condenser is shown in Figs. 287 and 288. If a galvanometer were connected in circuit with a condenser and a direct E. M. F. applied, it would be noticed that just after the pressure was applied a current would flow for a short interval; also that if the terminals were disconnected from the source of current and connected together, the galvanometer

would be deflected in the reverse direction. There is a momentary current just at the instant the condenser is *charged*, and a reverse momentary current when it is *discharged*.

If a condenser be connected to a source of alternating current and a galvanometer connected in the circuit, it will be found that the galvanometer indicates a current as long as the alternating E. M. F. is applied to the circuit. The circuit acts just as if it were complete, and we have the peculiar effect of a current apparently flowing through a circuit which has a complete break in it, for it will be remembered that there is no connection between adjacent plates of the condenser.

What actually occurs is that the condenser is charged to a potential equal to the *maximum* applied E. M. F. during the first quarter of a cycle, discharged during the second quarter, charged again, but in the opposite direction, during the third quarter of the cycle, and discharged during the fourth quarter, this continuing as long as the condenser remains in circuit and the alternating current continues to operate, the condenser being charged and discharged continuously, so that current will flow in the circuit in spite of the fact that the two sides of the condenser are insulated from each other, which prevents the actual flow of current through it. Thus we see that a condenser is equivalent to a closed circuit having a certain resistance, or in other words, it has an apparent resistance in ohms which is called its reactance, corresponding to that due to inductance. The flow of current increases directly with the capacity and with the frequency, therefore the reactance is inversely proportional to these quantities. Calling K capacity in farads, reactance in ohms is :

$$\text{Reactance } Xk = \frac{1}{2\pi f K} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(124)}.$$

Prob. 145: What would be the reactance of a 25 microfarad condenser to an alternating current of 60 cycles?

By Formula (124)

$$Xk = \frac{1}{2\pi f K} = \frac{1}{2 \times 3.1416 \times 60 \times .000025} = \frac{1}{.0094} = 106.38 \text{ ohms.}$$

$$f = 60 \text{ cycles} ; \ 25 \text{ microfarads} = .000025 \text{ farad.}$$

Most circuits possess to a greater or less degree the same property as a condenser, namely that of holding a certain

charge or quantity of electricity, and this has a marked influence upon the behavior of an alternating current flowing in the circuit. The capacity of most circuits met with in practice is quite small in comparison with their inductance and resistance, consequently its effect is not usually so noticeable; however in some cases, especially in underground cable work and long overhead lines, these effects become important. Ordinary electrical devices, such as lamps, motors, etc., have little electrostatic capacity.

The important difference between capacity and inductance is that capacity apparently increases the current and inductance decreases it. Capacity, like self-induction, can produce some very peculiar effects in an alternating current circuit in addition to the peculiarity already referred to, namely that of a current apparently flowing through a circuit with a break in it.

399. Peculiarities Due to Self-Induction and Capacity.

Exp. 103: Connect an incandescent lamp, L, Fig. 389, in series with a coil, M, which has a considerable amount of self-induction. Connect the two across a 110-volt alternating current circuit. Meas-

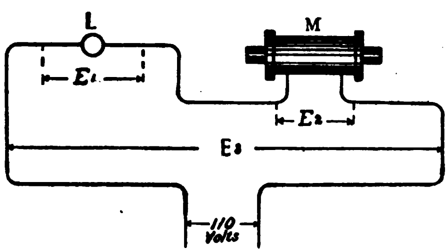

Fig. 389.

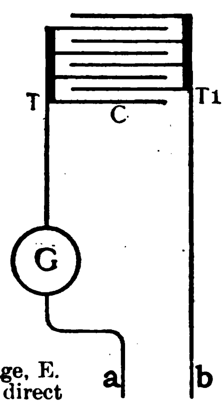

Fig. 390.

ure the voltage across the lamp L, and across the coil, M, add the results, and you find you get the apparently impossible result that the arithmetical sum is greater than the line voltage, E. Now if these two devices are connected across a direct current circuit and the drop on the lamp added to the drop on the coil the sum of the two would, of course, be equal to the line voltage, 110 volts. (See ¶403.)

Exp. 104: Fig. 390 shows another condition where alternating currents exhibit a peculiarity. If we take a condenser, C, and apply a direct

current to the terminals, T, T1, no current would flow unless the insulation broke down. If a galvanometer, G, is connected in the circuit, it will be noticed that just after the pressure is applied a current would flow for a short interval; also if the terminals, *a* and *b*, are disconnected from the source of the current and connected together, the galvanometer will give a deflection in the reverse direction, there being a momentary current just at the moment the condenser is charged and a reverse momentary current when it is discharged. If we now substitute a 110-volt lamp in place of the galvanometer and apply an alternating pressure of 110 volts to the terminals, *a b*, we find our lamp is lighted, and we have the peculiar effect of a current apparently flowing through a circuit which has a complete break in it.

What actually occurs is that when the current flows in one direction the condenser is charged, and when the current reverses the condenser discharges through the lamp, the action taking place so rapidly that the lamp is illuminated as if connected directly to the alternating pressure; if a direct current is now applied to the terminals, *a b*, the lamp will not be lighted, as the current is only a momentary one at the instant the pressure is applied.

Exp. 105: Fig. 391 shows an arrangement that illustrates a peculiar effect of self-induction and capacity combined. l_1 is an incandescent lamp, and l_2 and l_3 are also lamps of the same kind as l_1. M is an adjustable self-induction made up of a coil that can be moved over an iron core. C is a condenser. M and C are each in series with a lamp, and are each in one of the branch circuits into which the main circuit is split.

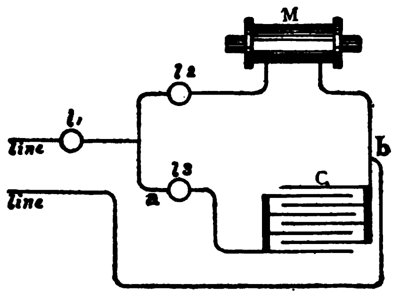

Fig. 391.

If this combination is connected to a direct current circuit of, say, 110 volts, no current at all would flow through branch *ab* on account of the condenser. If, however, alternating current is applied, current will flow through each branch. The striking point is that if M is adjusted to the proper amount, the peculiar result is obtained that l_1 can be made to burn at a dull red while lamps l_2 and l_3 burn up to full brightness. In other words, the sum of the two currents through l_2 and l_3 is less than either current singly, and the current flowing in the main circuit is less than the current flowing in either of the branch circuits. Such a result would, of course, be impossible with direct currents. (See ¶ 403.)

The above experiments illustrate a few cases where alternating currents differ in their behavior from direct currents. These effects are due to the fact that the current is continually changing and that either self-induction or capacity is present in the circuit.

The student is advised to read again ¶ 298.

400. Impedance Due to Inductance, Capacity and Resistance.—When a circuit contains both inductance and capacity, the net reactance is equal to the arithmetical difference between the inductive reactance, Xl, and the capacity reactance, Xk.

Therefore the impedance of a circuit containing inductance, capacity and resistance is :

$$\text{Imped.} = \sqrt{\text{Resist.}^2 + (\text{Induct. React.} - \text{Capac. React.})^2}$$

$$\mathbf{Z} = \sqrt{\mathbf{R}^2 + (\mathbf{X}l - \mathbf{X}k)^2} \quad . \quad . \quad . \quad (125.)$$

Prob. 146: What would be the combined impedance of a circuit having a coil of 4 ohms resistance and inductance of .01 henry in series with a condenser of 25 microfarads? Frequency of current 120 cycles.

By Formula (118) $Xl = 2\pi fL = 6.28 \times 120 \times .01 = 7.53$ ohms.
By Formula (124)

$$Xk = \frac{1}{2\pi fK} = \frac{1}{6.28 \times 120 \times .000025} = 53.07 \text{ ohms.}$$

By Formula (125) $Z = \sqrt{R^2 + (Xl - Xk)^2} = \sqrt{4^2 + (7.53 - 53.07)^2}$
$= \sqrt{16 + 2073.89} = 45.71$ ohms;

inductive reactance $(Xl) = 7.53$ ohms, capacity reactance $(Xk) = 53.07$ ohms, $R = 4$ ohms.

It is obvious that when Xl and Xk are equal the difference between them is zero, making the impedance, Z, equal to $\sqrt{R^2}$, which of course is R. When this is the case the circuit operates as though there were neither inductance nor capacity present, the current rising and falling in unison with the E. M. F. This may be made clearer by the use of the triangular diagram shown in Fig. 392; A, in the figure, shows the relation of capacity reactance, resistance and impedance. It will be observed that the line representing capacity reactance projects downward from the horizontal line, while the inductive reactance line (Fig. 388) projects upward; this indicates the opposite properties, inductance and capacity, as regards their effect on the E. M. F. and current in the circuit. When a circuit contains both inductance and capacity the *difference* between the lengths of the lines represent-

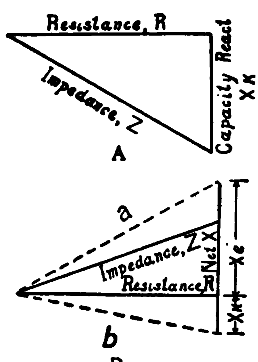

Fig. 392.

ing inductive and capacity reactances will represent the resultant or net reactance, X, of the circuit, as shown in B, Fig. 392.

In the figure the capacity reactance, X*k*, is one-third as great as the inductive reactance, X*l*; the resultant or net reactance, therefore, is two-thirds as great as the inductive reactance, and the impedance line is drawn from the base line to a point two-thirds up the line representing inductive reactance. The dotted line, *a*, shows what the impedance would be if there were no capacity in the circuit, and the dotted line, *b*, shows what the impedance would be if the inductance were not present. It is obvious that if the line, X*l*, and the line, X*k*, were of equal length their difference would be zero, and the impedance line would be identical with the resistance line, indicating the equality between resistance and impedance that the formula would indicate under the same conditions.

401. Ohm's Law for Alternating Current Circuits.—In dealing with direct current systems the relation existing between the pressure, current strength and resistance is fully explained by Ohm's Law, *i. e.*, $I=\frac{E}{R}$. Ohm's Law, however, cannot be applied in the same form to alternating current circuits, since the current no longer depends simply upon the resistance and E. M. F., but also depends on the frequency, *f*, inductance and capacity that may be contained in the circuit; so that Ohm's Law for alternating current circuits may be summarized as follows:

First.—*The current strength in any circuit is equal to the electromotive force applied to the circuit divided by the impedance of the circuit.**

Let **E** = E. M. F. potential difference, available pressure applied to any circuit.

Z = Impedance of the circuit expressed in ohms.

I = Current strength to be maintained

Then, by above statement,

$$\textbf{Current} = \frac{\textbf{Pressure}}{\textbf{Impedance}}, \textbf{ or } \mathbf{I} = \frac{\mathbf{E}}{\sqrt{\mathbf{R}^2+(2\pi \mathbf{f} \mathbf{L})^2}},$$

$$\textbf{or } \mathbf{I} = \frac{\mathbf{E}}{\mathbf{Z}} \; . \; . \; . \; . \; . \; . \; (126).$$

*Ohm's Law, as stated above, applies to alternating currents flowing in any circuit and bears the same relation and importance to alternating current problems that Ohm's Law $I = E \div R$ does to direct current problems, the essential difference between the two formulas being in the calculating of Z.

Prob. 147.—What current will flow through a coil of 7 ohms resistance and 24 ohms reactance when connected across an E. M. F. of 110 volts, 60 cycles? What current would flow if the coil were connected across 110 volts direct current?

By Formula (120) $Z = \sqrt{R^2 + X^2} = \sqrt{7^2 + 24^2} = \sqrt{49 + 576} =$ 25 ohms.

By Formula (125) $I = \frac{E}{Z} = \frac{110}{25} = 4.4$ amp. (*a*).

By Formula (28) $I = \frac{E}{R} = \frac{110}{7} = 15.7$ amp. (*b*).

Second. *The electromotive force of known frequency required to maintain a certain current strength in a circuit of known impedance, is numerically equal to the product of the current strength and the impedance.* $E = I \times Z$.

By the above statement,

$$\textbf{Pressure} = \textbf{Current Strength} \times \textbf{Impedance},$$
$$\mathbf{E} = \mathbf{I} \times \sqrt{\mathbf{R}^2 + (2\pi\mathbf{f}\mathbf{L})^2},$$
$$\mathbf{E} = \mathbf{I} \times \mathbf{Z} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (\mathbf{127}).$$

Prob. 148.—What E. M. F. would be required from an alternator of 60 cycles to send a current of 5 amperes through a coil of 4 ohms resistance and .02 henry inductance?

By Formula (120) $Z = \sqrt{R^2 + (2\pi f L)^2} = \sqrt{4^2 + (6.28 \times 60 \times .02)^2}$ $= \sqrt{4^2 + 7.53^2} = \sqrt{16 + 56.7} = 8.52$ ohms impedance.
By Formula (127) $E = I \times Z = 5 \times 8.52 = 42.6$ volts.

Third. *The impedance required to be inserted in any circuit so that a given current will flow by reason of a known pressure, is equal to the pressure to be applied divided by the current strength that is to be maintained.* $Z = \frac{E}{I}$.

By the above statement,

$$\textbf{Impedance} = \frac{\textbf{Pressure}}{\textbf{Current Strength}}.$$
$$\text{or, } \sqrt{\mathbf{R}^2 + (2\pi\mathbf{f}\mathbf{L})^2} = \frac{\mathbf{E}}{\mathbf{I}},$$
$$\text{or, } \mathbf{Z} = \frac{\mathbf{E}}{\mathbf{I}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (\mathbf{128}).$$

Prob. 149: What would be the impedance of a circuit having a pressure of 500 volts across it and a current of 6.5 amperes flowing?

By Formula (128) $Z = \frac{E}{I} = \frac{500}{6.5} = 76.9$ ohms impedance.

The similarity between the above formulæ and Ohm's

Law formulæ for direct currents will be quite apparent. With direct currents the value of the *resistance*, R, may be calculated from the physical dimensions of the wire only, but not so with *impedance* (the total opposition offered to the flow of an alternating current), since it does not simply depend upon the physical dimensions of the wire, but also, upon any *inductance* or capacity that the wire may possess. The *impedance*, however, may be measured by the same method as the resistance of a direct current circuit (¶241, page 247), using, of course, an alternating current voltmeter and ammeter, the impedance being calculated from $Z = E \div I$.

Then if the *reactance* is to be found, knowing the ohmic resistance of the circuit or device, it can be calculated from Formula (122) and the *inductance* found from Formula (119), providing the frequency of the current is known.

402. Impedances in Series.—When several inductive devices are connected in series on an alternating current circuit, the total impedance of the group cannot be determined by adding the individual impedances arithmetically, as is done with resistances in direct current work. The impedance of each device must be resolved into its component resistance and reactance.

To Find the Total Impedance of a Number of Impedances Connected in Series:

Find the sum of the resistances connected, and the sum of the reactances; then find the sum of the squares of the total resistance and reactance, and extract the square root of that sum.

$$Z = \sqrt{(R_1 + R_2 + R_3, \text{etc.})^2 + (X_1 + X_2, \text{etc.})^2}, \quad . \quad . \quad \textbf{(129)}.$$

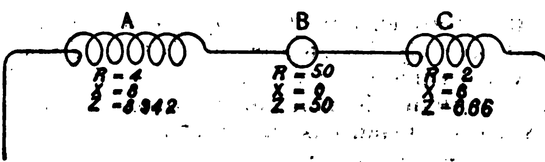

Fig. 393.

Prob. 150: Two inductive and one non-inductive devices are connected in series, Fig. 393, the coils, A and C, being the inductive parts of the circuit. The values of the resistance, reactance and impedance of each part of the circuit are inscribed in the figure. What is the total impedance of the devices so connected?

The non-inductive device, B, has no reactance, of course, so that its impedance is equal to its resistance. If we add the three impe-

dances in the figure we obtain the arithmetical sum of 65.6 ohms, the correct sum, or total impedance, is

By Formula (129) $Z = \sqrt{(R_1 + R_2 + R_3, \text{etc.})^2 + (X_1 + X_2, \text{etc.})^2}$ $= \sqrt{(4 + 50 + 2)^2 + (8 + 6)^2} = \sqrt{56^2 + 14^2} = 57$ ohms.

403. Impedances in Parallel.—When inductive devices are connected in parallel, which is the most frequent method in practice, the joint impedance of any given group of devices is determined by a similar method to that described in ¶402; but instead of considering the separate resistances and reactances, the opposite properties, *conductance* and *susceptance*, are considered. In direct current work, conductance, ¶153, is the reciprocal of resistance; in alternating current work, the actual conductance of an inductive circuit is not taken, but a value termed the effective conductance is substituted.

TO FIND EFFECTIVE CONDUCTANCE (G) : *Divide the resistance by the sum of the squares of the resistance and reactance.*

$$G = \frac{R}{R^2 + X^2} \quad . \; . \; . \; . \; . \; (\mathbf{130}).$$

TO FIND SUSCEPTANCE (S) : *Divide the reactance by the sum of the squares of the resistance and reactance.*

$$S = \frac{X}{R^2 + X^2} \quad . \; . \; . \; . \; . \; (\mathbf{131}).$$

The reciprocal of impedance is called *admittance*, represented by Y, and equal to the current divided by E. M. F. or

$$Y = I \div E \; . \; . \; . \; . \; . \; . \; (\mathbf{132}.)$$

The relation between *admittance, effective conductance* and *susceptance* is precisely the same as that between impedance, resistance and reactance, explained in ¶397, Fig 388. The formula for admittance is therefore the same as that for impedance, when conductance is substituted for resistance and susceptance for reactance; thus :

$$Y = \sqrt{G^2 + S^2} \quad . \; . \; . \; . \; (\mathbf{133}).$$

TO FIND THE JOINT IMPEDANCE OF A NUMBER OF DEVICES CONNECTED IN PARALLEL :

(*1*) *Find the conductances and susceptances of the different devices paralleled.* (*2*) *Find the sum of the conductances.* (*3*)

Find the sum of the susceptances. (4) Extract the square root of the sum of the squares of the total conductance and susceptance, which gives the admittance. (5) Since impedance is the reciprocal of admittance, one divided by admittance ($\frac{1}{Y}$) *will give the joint impedance of the circuit, or,*

$$\text{Joint impedance} = \frac{1}{\sqrt{G^2 + S^2}} \quad . \quad . \quad (134).$$

Prob. 151: What would be the joint impedance of the three devices in Fig. 393 if they were connected in parallel?

Effective conductance coil A

By Formula (130) $G = \frac{R}{R^2 + X^2} = \frac{4}{16 + 64} = .05$, conductance of A, and its susceptance

By Formula (131) $S = \frac{X}{R^2 + X^2} = \frac{8}{16 + 64} = .1$, susceptance of A.

Since lamp, B, is non-inductive, its effective conductance is equal to its actual conductance, *i. e.*, the reciprocal of its resistance, $\frac{1}{50} = .02$.

By Formula (130) Conductance of coil $C = \frac{2}{4 + 36} = .05$.

By Formula (131) Susceptance of coil $C = \frac{6}{4 + 36} = .15$.

Sum of all the conductances $= .05 + .02 + .05 = .12$, total conductance.

Sum of all the susceptances $= .1 + .15 = .25$, total susceptance.

Admittance (Y) by Formula (133) $Y = \sqrt{G^2 + S^2} = \sqrt{.12^2 + .25^2} = .277$, since impedance is the reciprocal of admittance,

$$\frac{1}{Y} = \frac{1}{.277} = 3.6 \text{ ohms, or}$$

by Formula (134) $\text{Impedance} = \frac{1}{\sqrt{G^2 + S^2}} = \frac{1}{\sqrt{.12^2 + .25^2}} = 3.6$ ohms.

404. Effective Values, Alternating Currents and E. M. F.'s.—We have already seen that an alternating current is one that is continually changing its value, as well as reversing its direction of flow. It passes through a certain set of values, called a *cycle*, over and over again, the current during each cycle passing through a large range of values from zero to its maximum value.

These instantaneous values are, as a rule, used very little in calculations. In alternating current apparatus and circuits, the E. M. F. available for work is not the maximum E. M. F., but the geometrical average of the E. M. F. values between zero and maximum. On the bases of the *sine curve*, this average is .707 of the maximum E. M. F., and is termed the *effective* E. M. F. In speaking of alternating current voltages, therefore, the *effective* E. M. F. is always meant, and it is this E. M. F. which is indicated by measuring instruments. The fluctuations of the current are obviously too rapid for the needle of

any instrument, however sensitive, to follow, and the instrument therefore indicates the geometrical mean of the fluctuating values.

When it is stated that an alternating current of, say, 10 amperes is flowing in a circuit, some average value must be implied, because, as a matter of fact, the current is continually alternating through a wide range of values.

Suppose we take the current represented by the wave in Fig. 394, and fix our attention on the cycle of values between A and E. We will also suppose that this current is furnished by a 60 cycle alternator, so that the complete set of values represented by the cycle included between A and E is passed over in $\frac{1}{60}$ second. Starting at A the current increases from zero to its maximum value at B, then decreases to zero again at C. The impedance of the circuit is such that the maximum value of the current is 10 amperes. It then passes through a similar set of values in the opposite direction. The question naturally arises: What are we going to call the value of this current? When the current is at its highest value in either direction it amounts to 10 amperes, but at all other instants it is smaller than this. It is necessary, then, that we understand clearly what is meant when we say an alternating current of so many amperes is flowing in a circuit. It is easy to see that we must mean some kind of average value, since from Fig. 394 we note that the current is continually passing through a range of values all the way from its zero value to its maximum value in either direction.

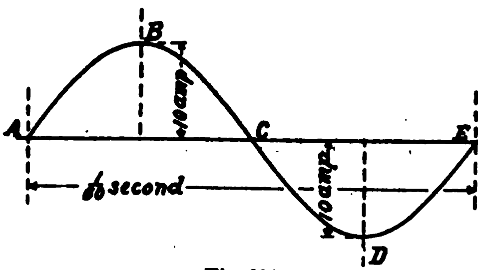

Fig. 394.

What we are most concerned with in the case of any kind of electric current is the *effect* which it is capable of producing in a circuit, and it has become the universal custom to express alternating currents in terms of the valne of the direct current which would produce the same power or heating effect. For example, suppose we send 10 amperes direct current through a resistance of 2 ohms. The watts dissipated in heat will be $I^2R = 10^2 \times 2 = 200$. Now suppose we send an alternating current through the same wire and adjust the current until the watts dissipated in heat are 200; we will then have what we call 10 amperes alternating current flowing through the wire. It is readily seen that the heating effect in a wire will increase and decrease as the current increases and decreases, because *at each instant the heating effect will be proportional to the square of the current at that instant.* Of course, the current varies so rapidly that to all intents and purposes the heating effect appears to be uniform, but it is not hard to see that the average heating effect must depend upon the heat produced at each instant during the cycle. If the frequency is

low enough, the variation in heating effect may be noticed, under favorable conditions.

If we take an incandescent lamp, the filament of which is very fine and quite sensitive to changes in the heating effect, and operate it from an alternator furnishing current at about 25 cycles, the lamp can be seen to flicker perceptibly, but if the frequency be raised above 40, the light becomes steady, so far as the eye can judge.

The variation in heating effect of an alternating current may be represented as shown in Fig. 395. Suppose we have a current represented by the full line wave, and that the current reaches its maximum value of 5 amperes during each half cycle or wave; also suppose that this current is sent through an impedance of 2 ohms. When the current is at its highest value (5 amperes) the watts expended in heat will be I^2R or $5^2 \times 2 = 50$. Lay off

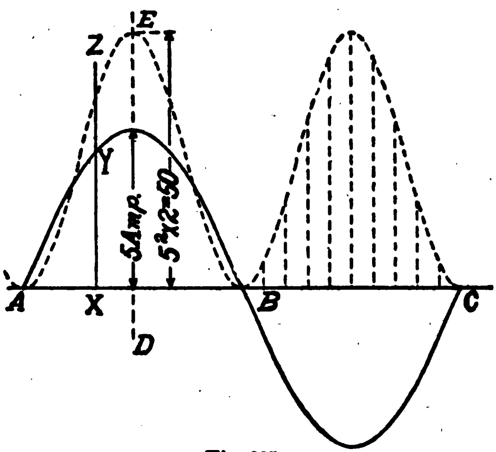

Fig. 395.

along DE a distance which will represent 50*. Now take another instant during the cycle, as shown at X, and scale off the value of the current XY. Having obtained this value, square it and multiply by 2, and then lay off XZ to the same scale used for DE to represent the watts expended in heating at the instant X.

We can do this for a number of points, and if we do so we obtain a curve something of the shape of that shown by the dotted line.

This shows that the heating effect varies up and down as the current changes. At first it rises rather slowly as we go along from point A, but as the current increases, the heating effect runs up rapidly, because it increases with the square of the current. Also note that this curve is altogether above the horizontal line, since in squaring the negative values of the current we multiply two negative quantities together, giving us a positive quantity.

Coming back to the question what constitutes the value of an alternating current, in Fig. 395 suppose we take one section of this curve between BC, divide it up by a number of equally spaced vertical lines, as shown; add these together and divide by the number of

*It makes no difference what scale is used in doing this, as long as we use the same scale in the laying off of the other points, as the object is merely to show how the heating varies.

lines. This will give us a fairly correct value of the average len of all the lines, just as the dividing up of an indicator card fro steam engine in the same way gives us the value of the mean ef tive pressure in the cylinder.

The average so obtained gives us the *average watts* expended in h or the average of all the values of I^2R.

Now R remains the same for all, so that the length of t line must represent to scale the *average of the squares of the values of the current* at the different instants, and the *squ root of the average of these squares* must give the value of t alternating current that will produce the same power or he ing effect as a corresponding direct current. This value an alternating current is sometimes called the *square root mean square value.* It is usually called *effective value* or *v tual value*, and is equal to the maximum value multiplied $\frac{1}{\sqrt{2}}$ or .707, or, maximum value of the current = effecti value $\times \sqrt{2}$, or 1.41.

If the maximum value of the current in Fig. 395 is 5 amperes, t effective value would be $5 \times .707 = 3.535$ amperes, the effective valı In other words, although our alternating current is continually r ing and falling between the limits + 5 amperes and — 5 amperes, only produces the same heating effect in the circuit as would 3.5 amperes direct current, because for a greater part of the time t alternating current is less than 5 amperes.

If we should put an alternating current ammeter into a circuit a the current indicated was 10 amperes, it would mean that the *effect value* of the current was 10 amperes and that the current w actually varying between + 14.1 and — 14.1 (10×1.41).

Care should be taken not to get the *effective value* of the curre mixed up with the *average value.* By the *effective* value is meant th value which will produce the same heating effect in a circuit as t same value of direct current.

By the *average* value is meant simply the average value of all t different values of t current during an alte nation, as shown in Fi 396. If we draw a numb of vertical lines, add the together and divide t the number of lines, v get the average lengt representing the avera current.

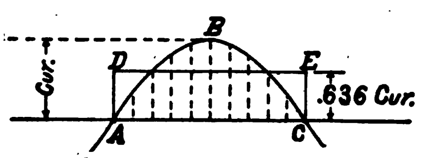

Fig. 396.

For a sine wave this average value is .636 times the maximu value, or *average value* = .636 maximum value.

The average length of the vertical lines in Fig. 396 multiplied t the length, AC, would give the area of the rectangle, ADEC, and th would be equal to the area bounded by the curve, ABC, and line, A(

The *average* value of the current is simply the *average of the values* during an alternation, but the *effective value is the square root of the average square* of all the different values.

For convenience the following relations are here given together:

Effective value $=$ .707 maximum value;
Average value $=$ .636 maximum value;
Effective value $=$1.11 average value.

The effective value as shown by the above relations is slightly greater than the average value.

In the same way, if an alternator delivers a pressure of 1000 volts as indicated by the switchboard instrument, the effective value is what is indicated, and the maximum value of the voltage would be equal to

$$\text{Effective value} \times 1.41, \text{ or } 1000 \times 1.41 = 1410 \text{ volts.}$$

The reader must not forget that this relation between the maximum and effective values applies to sine curves of E. M. F. and current only. For other shapes of waves the relation might be quite different. A wave with a sharp peak would, for example, have a maximum value which would be much higher, compared with the effective value, than given above.

405. Components of Impressed E. M. F.—In inductive alternating current circuits there are several distinct E. M. F.'s, the resultant of which is the applied E. M. F. It has been stated that there is a reactive or counter E. M. F. produced by the self-induction of the circuit; to overcome this and allow the current to pass, a component of the impressed E. M. F. must be used to overcome the counter E. M. F. of self-induction. The component of the impressed E. M. F. necessary to overcome the counter E. M. F. of self-inducton will be equal and in direct opposition to it.

Another component is required to overcome the *resistance* of the circuit, and from Ohm's Law, E $=$ I $\times$ R, we may for convenience imagine the resistance to set up a counter E. M. F. which is opposed to the impressed E. M. F., same as the E. M. F. of self-induction. The imaginary counter E. M. F., then, is directly opposed to the current, consequently the component of the impressed E. M. F. necessary to overcome resistance must be *in phase with the current*, that is, in the same direction as the current, Fig. 397.

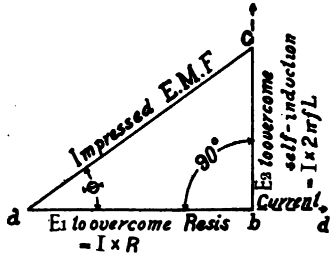

Fig. 397.

The relations between the impressed or applied E. M. F., counter E. M. F. of self-induction and E. M. F. to overcome resistance may be shown by means of a triangle, as in Fig. 388, the only difference

in the values being that all three of the former values hav multiplied by the current, so that the relations are unchanged

As stated above, we consider the impressed E. M. F. to b of two parts or components, one in phase with the current a other at right angles to it. The part required to overcome ance and in phase with the current is equal to $I \times R$ and repre by the line, ab, in Fig. 397. The part required to overcon counter E. M. F. of self-induction and at right angles to the c is equal to $I \times 2\pi fL$ and is represented by the line, bc, at angles to ab, the line, ac, representing to scale the imp E. M. F.

Now since abc is a right angle triangle, it follows the length $ac = \sqrt{ab^2 + bc^2}$; and since ac = impr E. M. F., ab = resistance, bc = reactance, the impr E. M. F. $= \sqrt{(I \times R)^2 + (I \times 2\pi fL)^2}$, or, letting Er = the drop due to resistance, and $Ex = I2\pi fL$, the reactive in volts, the formula may be written

$$\text{E. M. F.} = \sqrt{Er^2 + Ex^2} \quad . \; . \; . \; (135)$$

Prob. 152: In Exp. 103, Fig. 389, suppose the drop on the la 46 volts, the drop on the inductive resistance 100 volts, what w be the applied E. M. F.?

By Formula (135)

E. M. F. $= \sqrt{Er^2 + Ex^2} = \sqrt{46^2 + 100^2} = \sqrt{12116} = 110.$

From the relations shown in Fig. 397 the following de tions may be given for resistance, reactance and impeda

Resistance is that quantity which, multiplied by the rent, gives that component of the impressed E. M. F. wl is in phase with the current.

Reactance is that quantity which, multiplied by the rent, gives that component of the impressed E. M. F. wl is at right angles to the current.

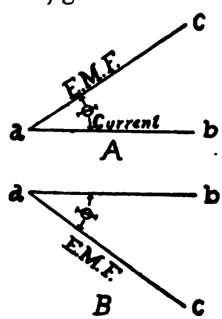

Fig. 398.

Impedance is that quantity wh multiplied by the current, gives impressed E. M. F.

The action of capacity in a circuit is ex the opposite to that of self-induction. induction makes the current lag behind E. M. F., while capacity makes the cur lead the E. M. F. It is possible, therefor have a circuit in which the effects of sel duction and capacity exactly neutralize other. For example: in A, Fig. 398, i represents the current, self-induction w make the current lag behind the E. M. F

the angle Φ. Capacity, on the other hand, would make the current lead the E. M. F., as shown in B, Fig. 398.

In Exp. 103, ¶ 399, Fig. 389, the E. M. F., E_1, across the lamp will be in phase with the current, L being a non-inductive resistance;

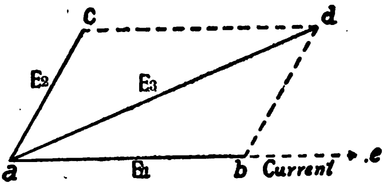

Fig. 399.

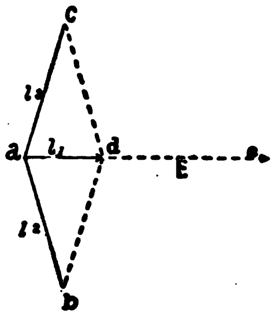

Fig. 400.

hence, in Fig. 399 we can represent E_1 by the line, ab, in phase with the current, ae. The E. M. F., E_2, across the inductive resistance, M, Fig. 389, will be represented by some such line, ac, considerably ahead of ab in phase.

The E. M. F., E_3, impressed by the circuit is the resultant of ab and ac, and is represented by the diagonal, ad. It is easily seen that the impressed E. M. F., E_3, is less than the arithmetical sum of E_2 and E_1, and also that E_3 would be equal to the arithmetical sum of E_1 and E_2 only when E_2 and E_1 were in phase with each other, as would be the case if both L and M were non-inductive, or if a direct current were applied to the circuit.

Take the case illustrated in Exp. 105, Fig. 391. The current in l_1 is the resultant of the currents in the two branches. The current in the inductive circuit will lag nearly one quarter of a cycle behind the E. M. F., and is represented in Fig. 400 by a line such as ab, the line, ae, representing the direction of the applied E. M. F., E. The current in the condenser will be nearly one quarter of a cycle ahead of the E. M. F., represented by the line, ac. L, Fig. 391, is supposed to be adjusted so that ac = ab. The current in lamp l_1 is, therefore, represented by the length of line, ad, and it is easily seen that because of the phase relation of ac and ab, this current may be much smaller than either of the currents in l_2 or l_3 taken by themselves.

406. Angle of Lag and Phase Difference.—In a circuit containing resistance and reactance, the self-induction also causes the current to lag behind the impressed E. M. F., the amount of lag depending upon the relative magnitude of the resistance and reactance. The amount of this lag is measured as an angle, called the *angle of lag*. It is customary to consider a cycle analogous to a circle, and to divide it into imaginary degrees; thus a quarter of a cycle is 90°, a half cycle 180°, and so on. This is convenient in that the

lagging of the current and reactive E. M. F. may be expressed in degrees of a circle instead of parts of a cycle. In Fig. 397 it is shown that the current which is in the direction of ad lags behind the impressed E. M. F. in the direction of ac by the angle ϕ, and it is termed the *angle of lag* of the current in the circuit, the angle here being 35°. The tangent of this angle is equal to the reactance ÷ resistance; hence, *if the resistance and reactance in a circuit are both known, the angle of lag may be calculated from*

$$\text{Tan. } \phi = \frac{\text{React.}}{\text{Resist.}} = \frac{2\pi f L}{R} \quad . \quad . \quad . \quad (\mathbf{136}).$$

From the relation $\frac{2\pi f L}{R}$, it is seen that the larger the reactance is, compared with the resistance, the larger will be the angle of lag, and if the reactance is small in comparison with the resistance the angle of lag will be small, the current being nearly in phase with the impressed E. M. F.

Prob. 153: By what angle would the current lag behind the E. M. F. in Prob. 148?

By Formula (136) $\text{Tan. } \Phi = \frac{2\pi f L}{R} = \frac{7.53}{4} = 1.88$ tangent.

From Table XI, page 173, tangent of 62° = 1.88; therefore the current in Prob. 148 lags 62° behind E. M. F.

The quarter of a cycle by which the reactive E. M. F. which is in the direction of bc lags behind the current is referred to as 90°, Fig. 397. The proportion of a cycle by which a current lags behind an impressed E. M. F., or by which one E. M. F. lags behind another, is termed the *phase* difference; phase differences are always expressed as degrees of a circle; thus, in Fig. 397 the phase difference between the impressed E. M. F. and E. M. F. to overcome resistance is the angle ϕ. As previously stated, this same angle is called the *angle of lag*, but this term is usually employed only in speaking of the lag of a current behind the E. M. F. which is applied to the circuit, the term *phase difference* on the other hand, is used only in referring to two E. M. F.'s or two currents that do not rise and fall in unison.

407. Determination of Power Expended in A. C. Circuits.—In direct current circuits the power expended is the product of the applied E. M. F. and the current that flows. In a circuit containing ohmic resistance only, the current does

not lag with respect to the E. M. F., and at any instant the power in watts is equal to E × I. With inductance in the circuit, the current lags behind the E. M. F., the current being positive when the E. M. F. is negative; hence the actual power is reduced, being equal to the algebraic sum of these quantities. When the reactance is great compared with the resistance, the current lags 90° behind the E. M. F., so that the actual power is zero.

TO FIND THE EFFECTIVE POWER WHEN THE E. M. F. AND CURRENT DIFFER IN PHASE, THAT IS, ONE LAGS BEHIND THE OTHER:

Multiply the effective E. M. F. by the effective current and this product by the cosine of the angle of lag.

$$\textbf{Power (W)} = \mathbf{E \times I \cos \Phi} \quad . \; . \; \mathbf{(137).}$$

The expression cos Φ* *is the cosine of the angle of lag, and is called the power factor, the power factor being the ratio of the real power to the apparent power, E × I.*

$$\text{Cos } \Phi = \frac{R}{Z} \; . \; . \; . \; . \; . \; . \; \mathbf{(138).}$$

Prob. 154: An alternator generating an E. M. F. of 1100 volts at a frequency of 60 cycles supplies to a system that has a resistance of 125 ohms and an inductance of .5 henry. (a) Find the value of the current. (b) Find the angle of lag. (c) Power factor. (d) Apparent watts and true watts.

By Formula (120) $Z = \sqrt{R^2 + (2\pi fL)^2} = \sqrt{125^2 + (6.28 \times 60 \times .5)^2}$ $= 226.09$ ohms impedance.

By Formula (128) $I = \frac{E}{Z} = \frac{1100}{226.09} = 4.86$ amp. (a)

By Formula (136) Tan. of angle $= \frac{2\pi fL}{R} = \frac{6.28 \times 60 \times .5}{125} = \frac{188.4}{125}$ $= 1.5.$

From Table XI, nearest tangent to 1.5 is 1.48 = 56°, angle of lag. (b)

Power factor = Cos Φ.

By Formula (138) Cos $\Phi = \frac{R}{Z} = \frac{125}{226} = .55$, power factor. (c)

Apparent watts:

By Formula (62) $W = E \times I = 1100 \times 4.86 = 5346$ watts. (d)

True watts:

By Formula (137) $W = E \times I \cos \Phi = 1100 \times 4.86 \times .55 =$ 2940.3 watts. (d)

To measure alternating current power it is necessary to know the angle of lag if separate volt and ammeters are used, or to employ a wattmeter, which gives the *true power* directly.

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*The cosine of any angle may be determined from a table of sines and cosines or from the ratio of R÷Z=cos Φ.

The effect of difference of phase, or the lagging of the current behind the E. M. F. upon the power expended, may be more clearly shown by the sine curves in Figs. 401 to 403. Fig. 401 shows a circuit containing ohmic resistance only, the current wave not lagging behind the E. M. F. wave; the power curve or wave lies wholly above the horizontal. The power is positive at all times, since the product of the positive values of E. M. F. and current as well as their negative values are always positive, and its effective value is simply the product of the effective E. M. F. and current, as read on a volt and ammeter; that is,

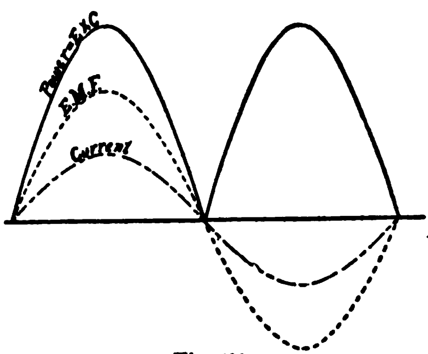

Fig. 401.

$$\text{Power (W)} = E \times I.$$

This represents the condition when the current is flowing through a non-inductive resistance. Suppose, however, that we have inductance in the circuit and the current lags behind the E. M. F. by an angle less than 90°, Fig. 402. The power curve is here constructed as before, but it is no longer wholly above the horizontal, due to the fact that the current curve is positive, while at the same instant the E. M. F. curve is negative; consequently the product of their values at that instant are negative, and the corresponding point on the power curve is below the horizontal. This means that during the intervals of time, ab and cd, negative work is being done; or, in other words, the circuit, instead of having work done on it, is returning energy to the system to which it is connected. In Fig. 403 the angle of lag has become 90°, the reactance being very great compared with the resistance. In this case the power curve lies as much above the horizontal as below it, the circuit returning as much energy as is expended in it, the negative power at c and d being equal to the positive power at a and b. The total work done in this case is, therefore, zero, and although a current is flowing,

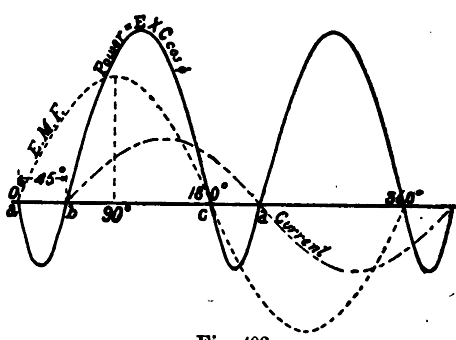

Fig. 402.

this current does not represent energy expended. Such a current at right angles to the E. M. F. is for these reasons known as a *wattless current*, because the product of such a current by the E. M. F. does not represent any watts expended.

The current may be looked upon as being resolved into two components, Fig. 404, one at right angles to the E. M. F., known as the *wattless component* of the current, and the other in phase with the E. M. F., known as the *power component*.

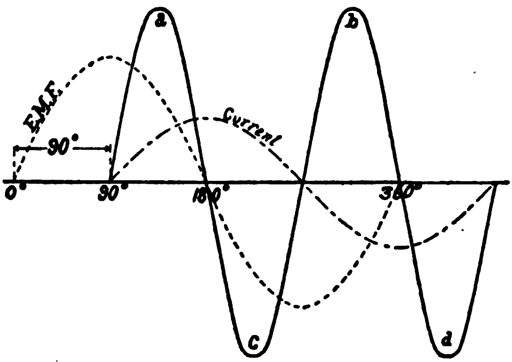

Fig. 403.

From Fig 404 it will be seen that the greater the angle of lag the greater will be the wattless component and the smaller the part which is expending power in the circuit.

Although wattless currents do not represent any power wasted, they are objectionable, as they merely load up the generator and lines, thus limiting their output as to current carrying capacity. For example, a generator might be furnishing current to a system having a very low power factor. The actual power delivered would be small, and not much power would be required to drive the dynamo. At the same time the current is circulating through the lines and the armature of the dynamo, thus loading up the lines and heating the machine. As the current output of the armature is limited to a great extent by this heating, it is seen that the useful current which may be taken from the dynamo is cut down by the presence of this *wattless component*. In practice, alternating-current apparatus are always designed so as to have as large a power factor as possible consistent with economy. It is possible to cut down the effect of self-induction by inserting a condenser in the circuit, thus cutting down the lag of he current and increasing the power factor.

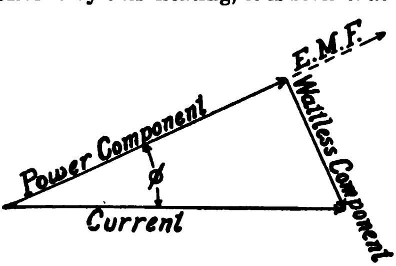

Fig. 404.

If the capacity of the condenser is sufficient it is possible to completely neutralize the effect of self-induction, in which case the current would be in phase with the E. M. F. and follow Ohm's Law.

QUESTIONS

1. How does an alternating current differ from a continuous or direct current?
2. What advantage has the alternating current over the direct current?
3. What do you understand by the term frequency?
4. How would you determine the frequency in cycles of any alternator?
5. Why does self-induction have such an important effect upon an alternating current?
6. What is impedance?
7. How would you represent graphically the relation existing between impedance, reactance and resistance?
8. If the frequency of an inductive circuit is doubled how will the current be affected, P. D. remaining the same?
9. What is meant by the capacity of a line or circuit?
10. What effect has capacity upon the flow of an alternating current?
11. What is the essential difference between capacity and inductance upon the flow of an alternating current?
12. Does Ohm's Law as applied to direct currents hold true for A. C.?
13. What factors beside resistance must be taken into consideration in determining the flow of A. C.?
14. For A. C. circuits what is the general form of Ohm's Law?
15. How can the impedance of a circuit be measured?
16. What is admittance?
17. What is meant by the effective value of an A. C.?
18. An ammeter in a certain circuit indicates 15 amperes. What would be the maximum value of this alternating current? *Ans.* 21.15 amp.
19. What are the components of the impressed E. M. F.?
20. Give a graphical illustration of the relations existing between the impressed E. M. F. and its components.
21. Define resistance, reactance and impedance.
22. What is meant by angle of lag?
23. Knowing the values of the resistance, inductance and frequency of a circuit, how would you determine the angle of lag?
24. Will the product of volts by amperes give the true power expended in an A. C. circuit? Why?
25. What is meant by the "power factor"?

PROBLEMS.

1. An alternator has 24 poles, its armature runs at a speed of 300 revolutions per minute. (*a*) What will be the frequency? (*b*) How many times would the current change its direction in one minute? *Ans.* (*a*) 60 cycles; (*b*) 7200.
2. (*a*) What would be the impedance of a circuit of 20 ohms resistance and 10 ohms reactance? (*b*) If a pressure of 110 volts, 60 cycles is applied to the above circuit what current will flow? (*c*) What is

the inductance of the above circuit? *Ans.* (*a*) 22.3 ohms; (*b*) 4.93 amp.; (*c*) .026 henry.

3. (*a*) What would be the impedance of the circuit in problem 2 if a 50 microfarad condenser was to be inserted in series? (*b*) How much current would flow? *Ans.* (*a*) 47.42 ohms; (*b*) 2.33 amps.

4. What E. M. F. must an alternator of 60 cycles supply to a circuit of negligible resistance and an inductance of .2 henry in order that a current of 5 amperes may flow? *Ans.* 376.8 volts.

5. (*a*) What would be the impedance of a circuit consisting of two coils, A and B, and two lamps, all connected in series; coil A has a resistance of 2 ohms and .5 ohm reactance; coil B has a resistance of 4 ohms and 7 ohms reactance; resistance of each lamp, 50 ohms. (*b*) What would be the impedance of each part of the circuit? *Ans.* (*a*) 106.17 ohms. (*b*) A = 2.06 ohms, B = 8.06 ohms, lamps = 50 ohms each.

6. What would be the impedance of the circuit if the coils and lamps in problem 5 were connected in parallel? *Ans.* 1.7 ohms.

7. (*a*) What will be the reactance of a coil of wire having a resistance of 4 ohms and an inductance of .02 henry, when connected to an alternating E. M. F. of 110 volts, 60 cycles? (*b*) What current will flow? (*c*) By what angle will the current lag behind the E. M. F.? (*d*) How many watts will be expended? (*e*) What is the value of the power factor of the circuit? (*f*) If the above coil is connected to 110 volts direct current, how much current will flow? *Ans.* (*a*) 7.54 ohms. (*b*) 12.89 amps. (*c*) 62°. (*d*) 652.23 watts. (*e*) .46 power factor. (*f*) 27.5 amps.

APPENDIX.

SUMMARY OF FORMULÆ.

The following formulæ have been derived in this book, and a problem solved to illustrate the manner of using each one.
In the text the formulæ are referred to by numbers, so that the formula corresponding to any number desired is readily obtained from this summary, as is also the page where the formula is fully explained.

Page		Formula Number
93.	$Q = I \times t$	(1).
93.	$I = \frac{Q}{t}$	(2).
94.	$t = \frac{Q}{I}$	(3).
96.	$I = \frac{W}{K \times t}$	(4).
96.	$W = I \times t \times K$	(5).
97	$t = \frac{W}{I \times K}$	(6).
99.	$I = \frac{V}{t \times K}$	(7).
99.	$V = I \times t \times K$	(8).
99.	$t = \frac{V}{I \times K}$	(9).
100.	$I = \frac{V \times h \times 273}{.1733 \times 76\,(273 + C^\circ) \times t}$	(10).
100.	$V = \frac{.1733 \times I \times 76\,(273 + C^\circ) \times t}{h \times 273}$	(11).
106.	$\text{Microhms} = \text{ohms} \times 1000000$	(12).
106.	$\text{Ohms} = \frac{\text{microhms}}{1000000}$	(13).

Page		Formula Number
106.	$\text{Megohms} = \dfrac{\text{ohms}}{1000000}$	(14).
106.	$\text{Ohms} = \text{megohms} \times 1000000$	(15).
109.	$R = \dfrac{K \times L}{d^2}$	(16).
111.	$C.M. = d^2$	(17).
111.	$d = \sqrt{C.M.}$	(18).
112.	$\text{Sq. mils} = c \times d$	(19).
112.	$\text{Sq. mils} = C.M. \times .7854$	(20).
112.	$C.M. = \text{sq. mils} \times 1.2732$	(21).
114.	$R = \dfrac{K \times L}{C.M.}$	(22).
114.	$L = \dfrac{R \times C.M.}{K}$	(23).
115.	$C.M. = \dfrac{L \times K}{R}$	(24).
115.	$\text{Pounds per mile (bare copper wire)} = \dfrac{C.M.}{62.5}$	(25).
115.	$\text{Pounds per foot (bare copper wire)} = \dfrac{C.M.}{62.5 \times 5280}$	(26).
115.	$\text{Pounds per mile (bare iron wire)} = \dfrac{C.M.}{72.13}$	(27).
119.	$I = \dfrac{E}{R}$	(28).
121.	$E = I \times R$	(29).
122.	$R = \dfrac{E}{I}$	(30).
123.	$I = \dfrac{E}{R + r}$	(31).
124.	$E = I \times r$	(32).
124.	$E = I \times (R + r)$	(33).
124.	$R = \dfrac{E}{I} - r$	(34).

Page		Formula Number
124.	$r = \frac{E}{I} - R$	(35).
130.	Total internal resistance of cells in series $= r \times ns$	(36).
130.	$I = \frac{E \times ns}{(r \times ns) + R}$	(37).
131.	Total internal resistance of cells in parallel $= \frac{r}{nq}$	(38).
132.	$I = \frac{E}{\frac{r}{nq} + R}$	(39).
136.	Total internal resistance of any combination of cells $= \frac{r \times ns}{nq}$	(40).
136.	$I = \frac{E \times ns}{\frac{r \times ns}{nq} + R}$	(41).
140.	$\left\{ \begin{array}{l} I = E \times K \\ E = \frac{I}{K} \\ K = \frac{I}{E} \end{array} \right\}$	(42).
141.	$J.R. = \frac{R}{nq}$	(43).
141.	$nq = \frac{R}{J.R.}$	(44).
142.	$R = J.R. \times nq$	(45).
143.	$J.R. = \frac{R \times R_1}{R + R_1}$	(46).
145.	$E = I + I_1 + I_2$ etc. $\times J.R.$	(47).
146.	Multiplying power of a shunt (n) $= \frac{G}{S} + 1$	(48)
147.	$Ig = \frac{I}{\frac{G}{S} + 1}$	(49).
147.	$S = \frac{G}{n - 1}$	(50).

Page		Formula Number
173.	$\frac{I}{I_1} = \frac{\tan d}{\tan d_1}$	(51).
176.	$I = \frac{H \times r}{N} \times \tan d$	(52).
177.	$I = K \times \tan d$	(53).
193.	Magnetising Force $= I \times T$	(54).
193.	$I = \frac{\text{Magnetising Force}}{T}$	(55).
193.	$T = \frac{\text{Magnetising Force}}{I}$	(56).
208.	$R = \frac{A}{A_1 - A} \times r$	(57).
212.	Horse Power of a steam engine $= \frac{P \times L \times A \times N}{33000}$	(58).
213.	$J = E \times I \times t$	(59).
213.	$J = I^2 \times R \times t$	(60).
214.	$J = \frac{E^2}{R} \times t$	(61).
215.	$W = E \times I$	(62).
215.	$I = \frac{W}{E}$	(63).
215.	$E = \frac{W}{I}$	(64).
218.	$H.P. = \frac{E \times I}{746}$	(65).
218.	$K.W. = \frac{E \times I}{1000}$	(66).
218.	Watts $= K.W. \times 1000$	(67).
220.	$W = I^2 \times R$	(68).
220.	$W = \frac{E^2}{R}$	(69).
220.	$R - \frac{W}{I}$	(70)

Page	Formula	Formula Number
221.	$I = \sqrt{\frac{W}{R}}$	(71).
221.	$R = \frac{E^2}{W}$	(72).
221.	$E = \sqrt{W \times R}$	(73).
222.	$H.P. = \frac{I^2 \times R}{746}$	(74).
222.	$H.P. = \frac{E^2}{746 \times R}$	(75).
222.	$E = \frac{H.P. \times 746}{I}$	(76).
222.	$I = \frac{H.P. \times 746}{E}$	(77).
222.	$R = \frac{E^2}{H.P. \times 746}$	(78).
222.	$K.W. = \frac{I^2 \times R}{1000}$	(79).
222.	$K.W. = \frac{E^2}{1000 \times R}$	(80).
223.	$W = \frac{E^2}{r}$	(81).
224.	$N = \frac{4 \times W \times r}{E^2}$	(82).
225.	$Eff. = \frac{R}{R + r}$	(83).
225.	$Eff. = \frac{W}{W + w}$	(84).
236.	$I = \frac{E - P.D.}{r}$	(85).
236.	$P.D. = \frac{R \times E}{R + r}$	(86).
236.	$r = \frac{E - P.D.}{I}$	(87).
244.	$\text{Unknown E.M.F.} = \frac{\text{E.M.F. Standard} \times AD}{AC}$	(88).

Page		Formula Number
250.	Unknown Resistance $X = \dfrac{\text{Res. of Standard} \times \text{Drop on X}}{\text{Drop on Standard}}$	(89).
251.	$R = r\left(\dfrac{d}{d_1} - 1\right)$	(90).
255.	Resistance of $D = \dfrac{\text{Res. of A} \times \text{length C}}{\text{length B}}$	(91).
258.	Resistance of $D = \dfrac{B \times C}{A}$	(92).
269.	Heat Units $(H) = .0009477 \times E \times I \times t$	(93).
269.	$H = .0009477\ I^2R\ t$	(94).
269.	$H = .0009477 \times \text{watts} \times \text{seconds}$	(95).
269.	$I = \dfrac{H}{.0009477 \times E \times t}$	(96).
269.	$t = \dfrac{H}{.0009477 \times E \times I}$	(97).
270.	$C^\circ = \dfrac{(F^\circ - 32) \times 5}{9}$	(98).
271.	$F^\circ = \dfrac{C^\circ \times 9}{5} + 32$	(99).
271.	$R_1 = R\,[1 + (T \times F^\circ \text{ Rise})]$	(100).
271.	$R_1 = R\,[1 - (T \times F^\circ \text{ Fall})]$	(101).
370.	Elec. Eff. $= \dfrac{W}{W + w + w_1}$	(102).
398.	$I = \dfrac{E - \mathcal{E}}{r}$	(103).
398.	$\mathcal{E} = E - (I \times r)$	(104).
399.	$W = \mathcal{E} \times I$	(105).
402.	Counter E. M. F. + $(I \times r)$ = applied E. M. F.	(106).
411.	$W = \dfrac{\dfrac{T \times F \times S}{33000} \times 746}{\%M}$	(107).
412.	$W_1 = \dfrac{\dfrac{\%G \times S \times T_1}{33000} \times 746}{\%M}$	(108).

Page	Formula	Formula Number
413.	Total watts required $= W + W_1$	(109).
436.	$C.M. = \frac{10.79 \times L \times I}{E}$	(110).
438	$E = \frac{10.79 \times L \times I}{C.M.}$	(111).
440.	$C.M. = \frac{10.79 \times L \times I}{4 \times E}$	(112)
441.	$C.M. = \frac{H.P. \times 746 \times L \times 10.79}{E \times e \times \%M}$	(113).
441.	$I = \frac{H.P. \times 746}{E \times \%M}$	(114).
441.	$H.P. = \frac{I \times E \times \%M}{746}$	(115).
448.	$f = P \times \frac{N}{60}$	(116).
448.	$f = P \times N$	(117).
450.	$X = 2\pi fL$	(118).
451.	$L = \frac{X}{2\pi f}$	(119).
451.	$Z = \sqrt{R^2 + (2\pi fL)^2}$	(120).
451.	$Z = \sqrt{R^2 + X^2}$	(121).
451.	$X = \sqrt{Z^2 - R^2}$	(122).
451.	$R = \sqrt{Z^2 - X^2}$	(123).
453.	$Xk = \frac{1}{2\pi fK}$	(124).
456.	$Z = \sqrt{R^2 + (Xl - Xk)^2}$	(125).
457.	$I = \frac{E}{Z}$	(126).
458.	$E = C \times Z$	(127).
458.	$Z = \frac{E}{I}$	(128).
459.	$Z = (\sqrt{R_1 + R_2 + R_3, \text{ etc.})^2 + (X_1 + X_2. \text{ etc.})^2}$	(129).

Page		Formula Number
460.	$G = \frac{R}{R^2 + X^2}$	(130).
460.	$S = \frac{X}{R^2 + X^2}$	(131).
460.	$Y = \frac{I}{E}$	(132).
460.	$Y = \sqrt{G^2 + S^2}$	(133).
461.	Joint Impedance $= \frac{1}{\sqrt{G^2 + S^2}}$	(134).
466.	E. M. F. $= \sqrt{Er^2 + Ex^2}$	(135).
468.	Tan $\Phi = \frac{2\pi fL}{R}$	(136).
469.	$W = E \times I \cos\Phi$	(137).
469.	$\cos\Phi = \frac{R}{Z}$	(138).

MENSURATION.

Some of the following formulæ are often used in electrical calculations.

Properties of The Sphere.

Let d = diameter;

r = radius;

c = circumference;

$\pi = 3.1416$.

Then:

$$\text{Volume} = \frac{4}{3}\pi r^3 = 4.1888 \times r^3.$$

$$\text{Volume} = \frac{1}{6}\pi d^3 = 0.5236 \times d^3.$$

$$\text{Volume} = \frac{1}{6}\frac{c^3}{\pi^2} = 0.01689 \times c^3.$$

$$\text{Volume} = \frac{1}{6} d \times \text{area of the surface.}$$

$$\text{Volume} = \frac{2}{3} d \times \text{area of the great circle.}$$

$$\text{Volume} = \frac{2}{3} \text{ volume of the circumscribing cylinder.}$$

Volume = 0.5236 volume of the circumscribing cube.

AREA OF THE SURFACE OF A SPHERE.

$$\text{Area} = 4\pi r^2 = 12.5664 \times r^2.$$

$$\text{Area} = \pi d^2 = 3.1416 \times d^2.$$

$$\text{Area} = \frac{c^2}{\pi} = .3183 \times c^2.$$

$$\text{Area} = d \times c.$$

Area = 4 × area of the great circle.

Area = area of a circle whose d is twice d of sphere.

Area = curved surface of the circumscribing cylinder.

$$\text{Area} = \frac{6 \times \text{volume}}{\text{d}}.$$

RADIUS OF A SPHERE.

$$\text{Radius} = \sqrt[3]{\frac{3 \text{ volume}}{4\pi}} = 0.62035 \sqrt[3]{\text{volume}}.$$

$$\text{Radius} = \sqrt{\frac{\text{area surface}}{4\pi}} = \sqrt{.07958 \times \text{area surface}}$$

$$\text{Circumference} = \sqrt[3]{6\pi^2 \text{ volume}} = \sqrt[3]{59.2176 \times \text{volume}}$$

$$\text{Circumference} = \sqrt{\pi \times \text{area of surface}}.$$

$$\text{Circumference} = \frac{\text{area surface}}{\text{d}}.$$

The Circle.

Circumference $= \pi$ d.

Diameter $= \frac{c}{\pi} = c \times 0.31831.$

Area $= d^2 \times \frac{\pi}{4} = .7854 \times d^2.$

Area $= c^2 \times .07958.$

Area $= r^2 \times \pi.$

Area $= \frac{d}{4} \times$ circumference.

The Ellipse.

Area = Product both d's $\times$ .7854.

The Cylinder.

Area = circumference $\times$ altitude plus area of both ends

Volume = area of base $\times$ altitude.

Table XXIII.

Recapitulation.

DEFINITIONS OF PRACTICAL ELECTRICAL UNITS.

Quantities to be Measured.	Synonyms.	Symbol.	Name of Practical Unit.	Comparative Values.	Remarks. Fundamental or absolute or C. G. S. Units are: Centimeter (C) for Length. Gramme (G) for Mass. Second (S) for Time.
Current.	Strength. Intensity. Rate of Flow. Coulomb per Sec. Volume (obsolete).	I	Ampere.	Coulombs ÷ Seconds. Volts ÷ Ohms.	One Ampere deposits .0003-286 gramme, or 004991 grain of copper per second on the plate of a copper voltmeter.
Quantity.	Ampere - Second.	Q	Coulomb.	Amperes × Seconds.	One hour = 3,600 seconds; hence one ampere-hour = 3,600 ampere-seconds, or = 3,600 coulombs.
Electromotive Force. Difference of Potential.	Pressure. Tension.	E M F or E	Volt.	Amperes × Ohms. Joules ÷ Coulombs.	One volt = .933 standard Daniell cell (zinc sulphate of a density of 1.4 and copper sulphate of a density of 1.1).
Resistance.		R	Ohm.	Volts ÷ Amperes.	One *legal* ohm is the resistance of a column of pure mercury, 1 square millimeter in section and 106 centimeters long, at °Centigrade. 1 *true* ohm = 1.00283 *legal* ohms.
Capacity.		K	Farad.	Coulombs ÷ Volts.	The microfarad, one-millionth of a farad, has been generally adopted as a practical unit; the farad is too large a unit for practical use.
Power Activity.	Electrical H.P Rate of doing Work. Effect. Work ÷ Time.	P or Pw. or HP	Watt. (Volt-ampere).	Volts × Amperes. (Amperes)^2 × Ohms. (Volts)^2 ÷ Ohms. Joules ÷ Seconds.	One watt = $\frac{1}{746}$ electrical horse power. One electrical horse power = $\frac{\text{volts} \times \text{amperes}}{746}$ One electrical horse power = $\frac{(\text{amperes})^2 \times \text{ohms}}{746}$ One electrical horse power = $\frac{(\text{volts})^2}{746 \text{ ohms}}$
Work, Heat, Energy.	Power×Time.	W or Wj.	Joule. (Volt-coulomb.)	Watts × Seconds. Volts × Coulombs. (Amperes)^2 × Ohms × Seconds. (Volts)^2 × Seconds ÷ Ohms	One joule is the work done or heat generated by a watt in a second. One joule is the heat necessary to raise .238 gramme of water 1° C.; or one joule = .238 calorie or therm. One joule = .7375 foot-pound in a second.

Table XXIV.—Equivalents of Units of Length.

	Millimeter	Centimeter	Meter	Kilometer	Mil	Inch	Foot	Yard	Mile (Statute)	Mile (Geog'h'l)
Millimeter	1	01	.001	000001	39.37079	.039371	.003281	.001094	.0000006	.0000007
Centimet'r	.10	1	1	.00001	393.7079	.3937079	.032809	.010936	.0000062	.000007
Meter	1000	100	1	.001	39,370.79	39.37079	3.28090	1.09363	.000621	.000716
Kilometer	1,000,000	100,000	1000	1		39,370.79	3280.899	1093.633	.621382	.716330
Mil	.025399	.0025399	.0000254		1	.001	.000083	.000028		
Inch	25.3994	2.53994	.025399	.0000254	1000	1	.083333	.027777	.0000158	.000015
Foot	304.7945	30.47945	.304795	.0003084	12000	12	1	.333333	.000189	.000104
Yard	914.3835	91.43835	.914384	.0009144	36000	36	3	1	.000568	.000493
Mile (Statute)		160,931.4	1.609.314	1.609314		63,360	5280	1760	1	.868382
Mile (Geog'ph.)		185,329	1853.29	1.85329		72,963.2	6080.27	2026.76	1.1516	1

Table XXV.

Equivalents of Units of Area.

	Square Millimet'r	Square Centime'r	Circular Mil	Square Mil	Square Inch	Square Foot
Square Millimeter	1	0.10	1973.6	1550.1	.00155	.0000108
Square Centimeter	100	1	197,361	155,007	155007	.001076
Circular Mil	.000507	.0000051	1	78540	8×10^{-7}	
Square Mil	.000645	.0000065	1.2733	1	.000001	
Square Inch	645.132	6.451	1,273,238	1,000,000	1	.006944
Square Foot	92,896.9	928.989			144	1

Table XXVI.

Equivalents of Units of Volume.

	Cubic Inch	Fluid Ounce	Gallon	Cubic Foot	Cubic Yard	Cu. Centimeter	Liter	Cubic Meter
Cubic Inch	1	.554112	.004329	.000578		16.3862	.016386	
Fluid Ounce	1.80469	1	.007812	.001044		29.5720	.029572	
Gallon	231	128	1	.133681	.00495	3785.21	3.78521	.003785
Cubic Foot	1728	957.506	7.48052	1	.037037	28315.3	28.3153	.028315
Cubic Yard	46,656	25,852.6	201.974	27	1	764,505	764.505	.764505
Cubic Centimeter	.061027	.033816	.000264	.000035		1	.001	.000001
Liter	61.027	33.8160	.264189	.035317		1000	1	.001
Cubic Meter	61027	33816	264.189	35.3169	1.3080		1000	

Table XXVII.

EQUIVALENTS OF UNITS OF WEIGHT.

	Grain	Troy Ounce	Pound Avs.	Ton	Milli-gram	Gram	Kilo-gram	Metric Ton
Grain	1	.020833	.000143		64.799	.064799	.000065	
Troy Ounce	480	1	.068041		31,103.5	31.1035	.031104	
Pound Avoird'pois	7,000	14.5833	1	.000447		453.593	.453593	.000454
Ton		32,666.6	2240	1			.001016	1.01605
Milligram	.015432	.000032	.000002		1	.001	.000001	
Gram	15.4323	.032151	.002205		1000	1	.001	
Kilogram	15,432.3	32.1507	2.20462	.000984	1,000,000	1000	1	.001
Metric Ton		32,150.7	2204.62	.98421		1,000,000	1000	1

Tables XXIV to XXVIII taken from Professor Sloane's Arithmetic by permission of the publisher.

Table XXVIII.—Equivalents of Units of Energy and Work.

	Erg	Meg-Erg	Gram Degree C	Kilogram Degree C	Pound Degree C	Pound Degree F	Watt Second	Gram Centime'r	Kilogram Meter	Foot Pound	Horse-Power-Second English	Horse-Power-Second Metric
Erg	1	$\frac{1}{10^6}$	$\frac{23888}{10^{12}}$	$\frac{23888}{10^{15}}$	$\frac{527}{10^{13}}$	$\frac{948}{10^{13}}$	$\frac{1}{10^7}$	$\frac{101,979}{10^8}$	$\frac{10,197}{10^{13}}$	$\frac{737,612}{10^{13}}$	$\frac{13411}{10^{14}}$	$\frac{13596}{10^{14}}$
Meg-Erg	10^6	1	$\frac{23888}{10^6}$	$\frac{23888}{10^9}$	$\frac{527}{10^7}$	$\frac{948}{10^7}$	0.1	1019.79	$\frac{101,979}{10^7}$	$\frac{737,612}{10^7}$	$\frac{13411}{10^8}$	$\frac{13596}{10^8}$
Gram Degree C	41,861,700	41.8617	1	.001	.002205	.003968	4.18617	42,684.3	.426,843	3.08777	.005,614	.005692
Kilogr'm Degree C	41,862×10^6	41,861.7	1000	1	2.2046	3.9683	4186.17	42,684,300	426,843	3087.77	5.61412	5.692
Pound Degree C	18,988×10^6	18,988.1	453.592	.453,592	1	1.8000	1398.81	19,363,900	193.639	1400.59	2.54652	2.58185
Pound Degree F	10,549×10^6	10,549	251.996	251,996	.555,556	1	1054.90	10,757,700	107.577	778.104	1.41474	1.43436
Watt Second	10^7	10	.238,882	$\frac{238,882}{10^8}$	.000,527	.000948	1	10,197.9	.101,979	.737,612	.001,341	.001,359
Gram Centimeter	980.596	.000981	.000,023	$\frac{2342}{10^{11}}$	$\frac{5164}{10^{11}}$	$\frac{9296}{10^{11}}$	.000,098	1	.00001	$\frac{723,328}{10^5}$	$\frac{13151}{10^{11}}$	$\frac{13333}{10^{11}}$
Kilogram Meter	981×10^6	98.0596	2.34247	.002,342	.005164	.009296	9.80596	100,000	1	7.23328	.013,151	.013,333
Foot Pound	13,557,300	13.5578	.323,859	.000,324	.000714	.001,285	1.35573	13,825.5	.138,255	1	.001,818	.001,843
Horse-Power Sec. English	745,650×10^4	7456.50	178.122	.178122	.39292	.70684	745.650	7,604,040	76.0404	550	1	1.01383
Horse-Power Sec. Metric	73,545×10^5	7354.5	.175685	175.685	.38732	.69717	735.447	7,500,000	75	542.475	.986,356	1

Table XXIX.

Comparative Table of Gauges.

Giving the respective diameter and area of each number.

Gauge No.	American Wire Gauge (Brown & Sharpe)		Birmingham Wire Gauge (Stubs)		Standard Wire Gauge	
	Diameter	Area	Diameter	Area	Diameter	Area
	Inches	Cir'lar Mills	Inches	Cir'lar Mills	Inches	Cir'lar Mills
7-0					0.500	250000.
6-0					0.404	215300.
5-0					0.432	186600.
4-0	0.4600	211600.	0.454	206100.	0.400	160000.
3-0	0.4096	167800.	0.425	180600.	0.372	138400.
2-0	0.3648	133100.	0.380	144400.	0.348	121100.
1-0	0.3249	105500.	0.340	115600.	0.324	105000.
1	0.2893	83690.	0.300	90000.	0.300	90000.
2	0.2576	66370.	0.284	80660.	0.276	76180.
3	0.2294	52630.	0.259	67080.	0.252	63500.
4	0.2043	41740.	0.238	56640.	0.232	53820.
5	0.1819	33100.	0.220	48400.	0.212	44940.
6	0.1620	26250.	0.203	41210.	0.192	36860.
7	0.1443	20820.	0.180	32400.	0.176	30980.
8	0.1285	16510.	0.165	27230.	0.160	25600.
9	0.1144	13090.	0.148	21900.	0.144	20740.
10	0.1019	10380.	0.134	17960.	0.128	16380.
11	0.09074	8234.	0.120	14400.	0.116	13460.
12	0.08081	6530.	0.109	11880.	0.104	10820.
13	0.07196	5178.	0.0950	9025.	0.092	8464.
14	0.06408	4107.	0.0830	6889.	0.080	6400.
15	0.05707	3257.	0.0720	5184.	0.072	5184.
16	0.05082	2583.	0.0650	4225.	0.064	4096.
17	0.04526	2048.	0.0580	3364.	0.056	3136.
18	0.04030	1624.	0.0490	2401.	0.048	2304.
19	0.03589	1288.	0.0420	1764.	0.040	1600.
20	0.03196	1022.	0.0350	1225.	0.036	1296.
21	0.02846	810.1	0.0320	1024.	0.032	1024.
22	0.02535	642.4	0.0280	784.	0.028	784.0
23	0.02257	509.5	0.0250	625.	0.024	576.0
24	0.02010	404.0	0.0220	484.	0.022	484.0
25	0.01790	320.4	0.0200	400.	0.020	400.0
26	.01594	254.1	0.0180	324.	0.018	324.0
27	.01420	201.5	0.0160	256.	0.0164	269.0
28	0.01264	159.8	0.0140	196.	0.0148	219.0
29	0.01126	126.7	0.0130	169.	0.0136	185.0
30	0.01003	100.5	0.0120	144.	0.0124	153.8
31	0.008928	79.70	0.0100	100.	0.0116	134.6
32	0.007950	63.21	0.0090	81.	0.0108	116.6
33	0.007080	50.13	0.0080	64.	0.0100	100.0
34	0.006305	39.75	0.0070	49.	0.0092	84.64
35	0.005615	31.52	0.0050	25.	0.0084	70.56
36	0.005000	25.00	0.0040	16.	0.0076	67.76
37	0.004453	19.83			0.0068	46.24
38	0.003965	15.72			0.0060	36.00
39	0.003531	12.47			0.0052	27.04
40	0.003145	9.888			0.0048	23.04
41					0.0044	19.36

TABLE XXX.—DECIMAL EQUIVALENTS

OF EIGHTHS, SIXTEENTHS, THIRTY-SECONDS AND SIXTY-FOURTHS OF AN INCH.

Eighths.	Thirty-Seconds.	Sixty-Fourths.	Sixty-Fourths
1/8 = .125	1/32 = .03125	1/64 = .015625	33/64 = .515625
1/4 = .250	3/32 = .09375	3/64 = .046875	35/64 = .546875
3/8 = .375	5/32 = .15625	5/64 = .078125	37/64 = .578125
1/2 = .500	7/32 = .21875	7/64 = .109375	39/64 = .609375
5/8 = .625	9/32 = .28125	9/64 = .140625	41/64 = .640625
3/4 = .750	11/32 = .34375	11/64 = .171875	43/64 = .671875
7/8 = .875	13/32 = .40625	13/64 = .203125	45/64 = .703125
Sixteenths.	15/32 = .46875	15/64 = .234375	47/64 = .734375
1/16 = .0625	17/32 = .53125	17/64 = .265625	49/64 = .765625
3/16 = .1875	19/32 = .59375	19/64 = .296875	51/64 = .796875
5/16 = .3125	21/32 = .65625	21/64 = .328125	53/64 = .828125
7/16 = .4375	23/32 = .71875	23/64 = .359375	55/64 = .859375
9/16 = .5625	25/32 = .78125	25/64 = .390625	57/64 = .890625
11/16 = .6875	27/32 = .84375	27/64 = .421875	59/64 = .921875
13/16 = .8125	29/32 = .90625	29/64 = .453125	61/64 = .953125
15/16 = .9375	31/32 = .96875	31/64 = .484375	63/64 = .984375

TABLE XXXI.

VOLTS LOST ON COPPER WIRE.

Table of volts lost or drop per ampere per 1,000 feet of conductor. (Calculated by E = I × R. Formula (99).) Copper wire, B. & S. gauge (70° F.).

Size, B. & S.	Volts Drop per Ampere per 1,000 Feet.	Size, B. & S.	Volts Drop per Ampere per 1,000 Feet.
0000	.0493	17	5.088
000	.0621	18	6.415
00	.0783	19	8.089
0	.0987	20	10.20
1	.1242	21	12.86
2	.1570	22	16.22
3	.1980	23	20.45
4	.2496	24	25.79
5	.3148	25	32.52
6	.3970	26	41.01
7	.5006	27	51.72
8	.6312	28	65.21
9	.7958	29	82.23
10	1.040	30	103.7
11	1.266	31	130.7
12	1.596	32	164.9
13	2.012	33	207.9
14	2.537	34	262.2
15	3.200	35	330.6
16	4.035	36	416.8

PROBLEM.—How many volts would be lost in carrying 10 amperes a distance of 2,000 feet on a No. 6 B. & S. Wire?

Solution, from Table XXXI: .3970 volt is lost per ampere per 1,000 feet, or .7940 volt per 2,000 feet for one ampere, or 7.9940 volts per 10 amperes, E = I × R.

Table XXXII.

Useful Equivalents for Electric Heating Problems.

By H. Ward Leonard, Elec. Eng.

Unit.	Equivalent Value in other Units.
1 K. W. Hour =	1,000 Watt hours 1.34 horse power hours 2,654,200 ft. lbs. 3,600,000 joules 3,412 heat units 367,000 kilogram metres .229 lbs. coal oxidized with perfect efficiency 3.53 lbs. water evaporated at 212° F 22.75 lbs. of water raised from 62° to 212° F 8 cents at usual rates for electric Heating
1 H. P. Hour =	.746 K. W. hours 1,980,000 ft. lbs. 2,545 heat units 273,740 k. g. m. .175 lbs. coal oxidized with perfect efficiency 2.64 lbs. water evaporated at 212° F 17.0 lbs. water raised from 62° F. to 212° F 6 cents at usual rates for electric heating
1 K. W. =	1,000 Watts 1.34 H. P. 2,654,200 ft. lbs. per hour 44,240 ft. lbs. per minute 737.3 ft. lbs. per second 3,412 heat units per hour 56.9 heat units per minute 9.48 heat units per second .2275 lbs. coal oxidized per hour 3.53 lbs. water evaporated per hour at 212° F
1 H. P. =	746 Watts .746 K. W. 33,000 ft. lbs. per minute 550 ft. lbs. per second 2,545 heat units per hour 42.4 heat units per minute .707 heat units per second .175 lbs. coal oxidized per hour 2.64 lbs. water evaporated per hour at 212° F
1 Joule =	1 Watt second .00000278 K. W. hour 102 k. g. m. .0009477 heat units .7373 ft. lbs.
1 Ft. Lb. =	1.356 joules .1383 k. g. m. .000000377 K. W. hours .0001285 heat units .0000005 H. P. hour
1 Watt =	1 joule per second .00134 H. P. .001 K. W. 3.412 heat units per hour .7373 ft. lbs. per second .003 lbs. of water evaporated per hour 44.24 ft. lbs. per minute
1 Watt per Sq. In. =	8.19 thermal units per sq. ft. per minute 120° F. above surrounding air (Japanned cast iron surface) 66° C. above surrounding air (Japanned cast iron surface)
1 Heat Unit =	1055 Watt seconds 778 ft. lbs. .252 calorie (Kg.-d.) 107.6 kilogram metres .000293 K. W. hour .000393 H. P. hour .0000688 lbs. coal oxidized .001036 lbs. water evaporated at 212° F
1 Heat Unit per Sq. Ft. per min. =	1221 Watts per square inch .0176 K. W. .0236 H. P.
1 Kilogram Metre =	7.23 ft. lbs .00000366 H. P. hour .00000272 K. W. hour .0093 heat units
1 Lb. Bituminous Coal Oxidized with perfect efficiency =	14,544 heat units 1.11 lbs. Anthracite coal oxidized 2.5 lbs. dry wood oxidized 21 cu. ft. illuminating gas 4.26 K. W. hours (theoretical value) 5.71 H. P. hours (theoretical value) 11,315,000 ft. lbs. (theoretical value) 15 lbs. of water evaporated at 212° F
1 Lb. Water Evaporated 212° F =	.283 K. W. hour .379 H. P. hour 965.7 heat units 103,900 k. g. m. 1,019,000 joules 751,300 ft. lbs. .0664 lbs. of coal oxidized

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(Figures refer to the numbered pages.)

C.

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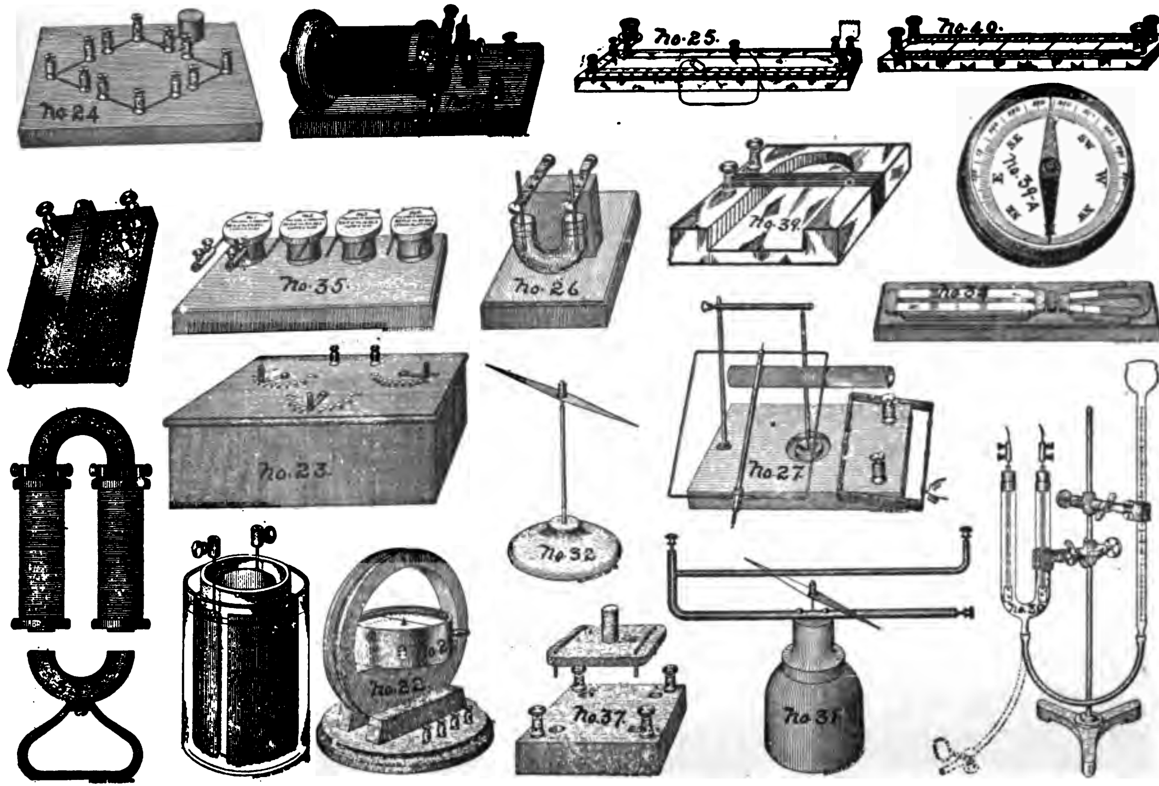

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